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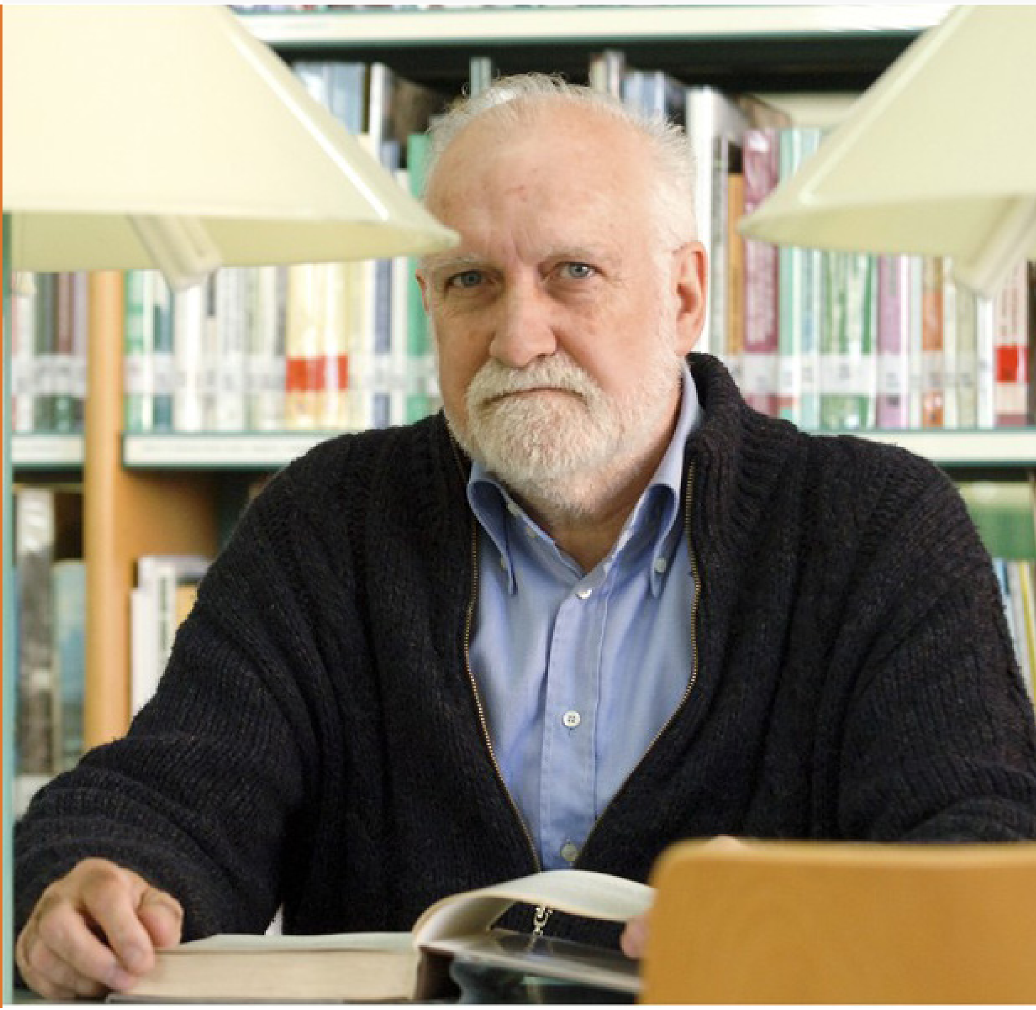
Jaume Porta Casanellas - RENS Soil Science



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Special Issue in tribute to the soil scientist Jaume Porta Casanellas, also including works derived from RENS2023 - XXXIII National Soil Meeting in Navarre, Spain (his last Congress).

Jaume co-founded and served as the secretary of the Editorial Board of the Spanish Journal of Soil Science and was a former president of the Spanish Society of Soil Science.

This Special Issue of the *Spanish Journal of Soil Science* was open to submissions on any aspect of Soil Science and Environmental Sciences, in tribute to Professor Jaume Porta Casanellas.

As he passed away in September 2023, just a few days after actively participating in his last scientific congress (RENS2023, Navarre, Spain), the Special Issue was also open to contributions directly related to this scientific meeting and sessions.

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SPECIAL ISSUE EDITORIAL
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Editorial: Jaume Porta Casanellas - RENS Soil Science

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Editorial on the Special Issue

Jaume Porta Casanellas - RENS Soil Science

This Special Issue is dedicated to the memory of the soil scientist Jaume Porta Casanellas, one of the most influential figures in Spanish soil science. He passed away shortly after the XXXII edition of one of the most emblematic congresses of the Spanish Society of Soil Science, the National Meeting of Soils (RENS2023), held in Navarre, Spain, which became his last scientific congress. Jaume Porta was a co-founder and Secretary of the Editorial Board of the Spanish Journal of Soil Science and also served as President of the Spanish Society of Soil Science, leaving a profound institutional and scientific legacy, strengthening deeply the connections between the Spanish and Latin American Soil Science Societies. As he passed away in September 2023, only a few days after his active participation in RENS2023, this Special Issue also includes a selection of contributions closely linked to that meeting and its scientific sessions, reflecting both his enduring influence and his final engagement with the soil science community. The selection of articles highlights the interdisciplinary nature of soil science.

Alcañiz et al. open this special issue with a contribution that gathers personal and professional reflections from disciples, colleagues and friends of Jaume Porta Casanellas, highlighting his scientific, educational and institutional legacy. The article reviews his leadership in Spanish soil science, his pioneering work on salt-affected and gypsum-rich soils, soil mapping, laboratory standardization, and soil education. Special emphasis is placed on his textbooks, international training initiatives, and his decisive role in strengthening scientific institutions, journals, and the dissemination of soil science knowledge.

Abbas et al. assess the effects of biochar (3%) combined with compost and animal manure (0.5%–1%) on soil carbon fractions, soil properties, and maize growth in low-fertility soil. Biochar combined with 1% compost significantly improved plant growth, soil organic matter, microbial biomass, and the carbon pool index. The findings highlight organic amendments as a sustainable strategy to restore degraded soils, enhance crop productivity, and support a circular economy under changing climate conditions.

Reyes-Sánchez examines soil science as an asset for interdisciplinary teaching approaches aimed at fostering values, scientific interest, and environmental responsibility in primary school children. Building on a previous methodological proposal, the study integrates knowledge construction with value formation through a playful, qualitative pedagogical strategy applied to 5th and 6th grade students. It compares children's perceptions of social, political, and environmental issues before and after the intervention, highlighting the role of science education in promoting sustainability-oriented attitudes.

Altés et al. analyse salt dynamics and drainage loads in a newly established irrigation district in the Ebro basin (NE Spain) during 2021–2023, including the severe 2023 drought. Monitoring two sub-basins showed that a 31% reduction in irrigation delivery led to a 73% decrease in drainage and a 70% reduction in salt exports. The results highlight the potential of irrigation restrictions to improve water and salt management, while also revealing associated yield losses.

Quintana-Esteras et al. evaluate the effects of prescribed burning and selective shrub clearing on subalpine soils and vegetation in the Central Pyrenees. Both treatments similarly increased soil pH and reduced several physical and chemical properties, while microbial functional diversity remained stable. Mechanical clearing enhanced soil microbial activity compared to burning. Two years after intervention, shrub cover remained low in both treatments, although prescribed burning resulted in more bare soil and reduced plant diversity than selective clearing.

Aguirre-Arcos et al. assess sap analysis as a rapid tool to diagnose the nutritional status of olive trees under integrated production in southern Spain. Trials across five farms showed clear seasonal nutrient fluxes in sap, influenced by climate and phenology. Comparisons among sap, leaf, and soil analyses highlighted potassium dominance in sap and climate-driven micronutrient variability. The results indicate that sap analysis complements traditional methods, supporting more precise and balanced fertilization strategies in olive orchards.

Usón Murillo et al. analyse initiatives to harmonize soil analytical methods in Spain through interlaboratory proficiency tests promoted by the Spanish Society of Soil Science (SECS) and partner institutions. Results from tests in 2019 and 2021 revealed significant methodological differences among laboratories, with partial improvements in performance and persistent weaknesses, particularly in organic matter and texture analyses. The study highlights the need for regular proficiency testing to improve analytical quality and ensure reliable soil data for sustainable soil management and policy implementation.

Pérez Moreira and Barral Silva in their article explore the rare but significant representation of soil in Western landscape painting. It identifies periods of naturalistic art, particularly in 17th-century Dutch painting and 19th-century European landscape schools, when artists depicted soils with unusual detail. Some works reveal recognizable soil horizons and features that can be interpreted using modern soil science. The study contextualizes these artistic representations historically and culturally, highlighting intersections between art, observation of nature, and soil knowledge.

Barreiro et al. study evaluates the influence of tree species on soil properties and microbial activity in 54 forest plantations in Galicia, NW Spain. Soils were generally acidic with high organic matter and low phosphorus contents. Moisture varied by vegetation: the driest soils under eucalyptus and birch, and the wettest under shrublands. Microbial respiration was highest in walnut soils and lowest in eucalyptus, while β-glucosidase activity remained unchanged. Results highlight that forest management, particularly tree species selection, affects soil microbial function and carbon stabilization, with implications for climate-adaptive forestry planning.

The special issue concludes with the study of Tierra et al. who investigate soil salinity in the rainfed landscapes of the "Saladas of Sástago-Bujaraloz" in the Central Ebro Basin, Spain. Analyses of 319 soil samples and electromagnetic sensor readings revealed highly variable and often extreme salinity, with 73% of samples very strongly saline. Vertical and horizontal variability was observed, with best electro-magnetic sensor readings correlations at 0–100 cm depth. The authors propose incorporating soil salinity as an agronomic criterion within the EU Common Agricultural Policy, recommending the exclusion of plots with ECe >10 dS m-1, representing more than half of their study area.

AUTHOR CONTRIBUTIONS

All authors listed have made a substantial, direct, and intellectual contribution to the work and approved it for publication.

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CONFLICT OF INTEREST

The author(s) declared that this work was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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ORIGINAL RESEARCH
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Soil Salinity, Agriculture, and Nature Conservation in Monegros, NE Spain

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Salinity is a determining factor for agriculture due to its effects on crops. The Common Agricultural Policy (CAP) of European Union does not take this concept into account when distributing monetary aid to farmers. The Central Ebro Basin (CEB) presents this problem due to the semiarid climate conditions and the composition of the soils, generating an economic suffocation in the rural areas of the region. The present work aims to evaluate salinity in a dry-farmed landscape surrounding the "Saladas of Sástago-Bujaraloz," a protected area under agricultural intensification with extreme saline conditions. We analyzed the saline composition of the soil of three saladas along transects and we surveyed the soil salinity with electromagnetic sensor (EMS) to facilitate the inspection of salinity in the field. The electrical conductivity (EC) ranged from slightly saline to very strongly saline. A 73% of the 319 soil samples analysed were very strongly saline (ECe >16 dS m^{-1}) and half of the very strongly saline soil samples were taken in crop areas. The mean EC1:5 varied from 15 dS m^{-1} in the saladas to a range of 3–4.6 dS m^{-1} in the crops. There was a noticeable variability of the vertical distribution of soil salinity and a high salinity range in the upper soil horizons of natural areas. In general, the salinity of the integrated 100 cm of soil depth (ECe100) was higher than that of 50 cm (ECe50). The correlation between the EMS readings and EC varied between saladas, between horizontal and vertical readings, and between integrated soil depths. The best relationship was found with a soil depth of 0–100 cm and with horizontal EMS readings. The identified salinity patterns are consistent and applicable in the whole area of about 150 saladas. The purpose is to suggest salinity as an agronomic criterion within the CAP regulations. A proposed new agri-environment-climate measure could include classifying plots with ECe >10 dS m^{-1} in more than 50% of the area as unsuitable for cultivation.

Keywords: arid lands, CAP, electromagnetic sensor, natura 2000, saline wetlands

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INTRODUCTION

Both in arid or semiarid inland regions and in coastal areas, soil salinity—whether natural or induced by human activities—occurs worldwide, as is the case in the Mediterranean region. Salinity threatens agriculture but, on the other hand, saline areas harbor organisms whose rarity and adapted metabolism give them a high scientific and social value. Therefore, knowing the distribution of soil salinity in the landscape is crucial not only for crop management and the protection of saline ecosystems, but also for the sustainability of agriculture.

Spain contains the largest surface of saline land in the European Union (Tóth et al., 2008; FAO, 2024). Traditionally, the saline areas supported low-income rainfed farming and extensive livestock

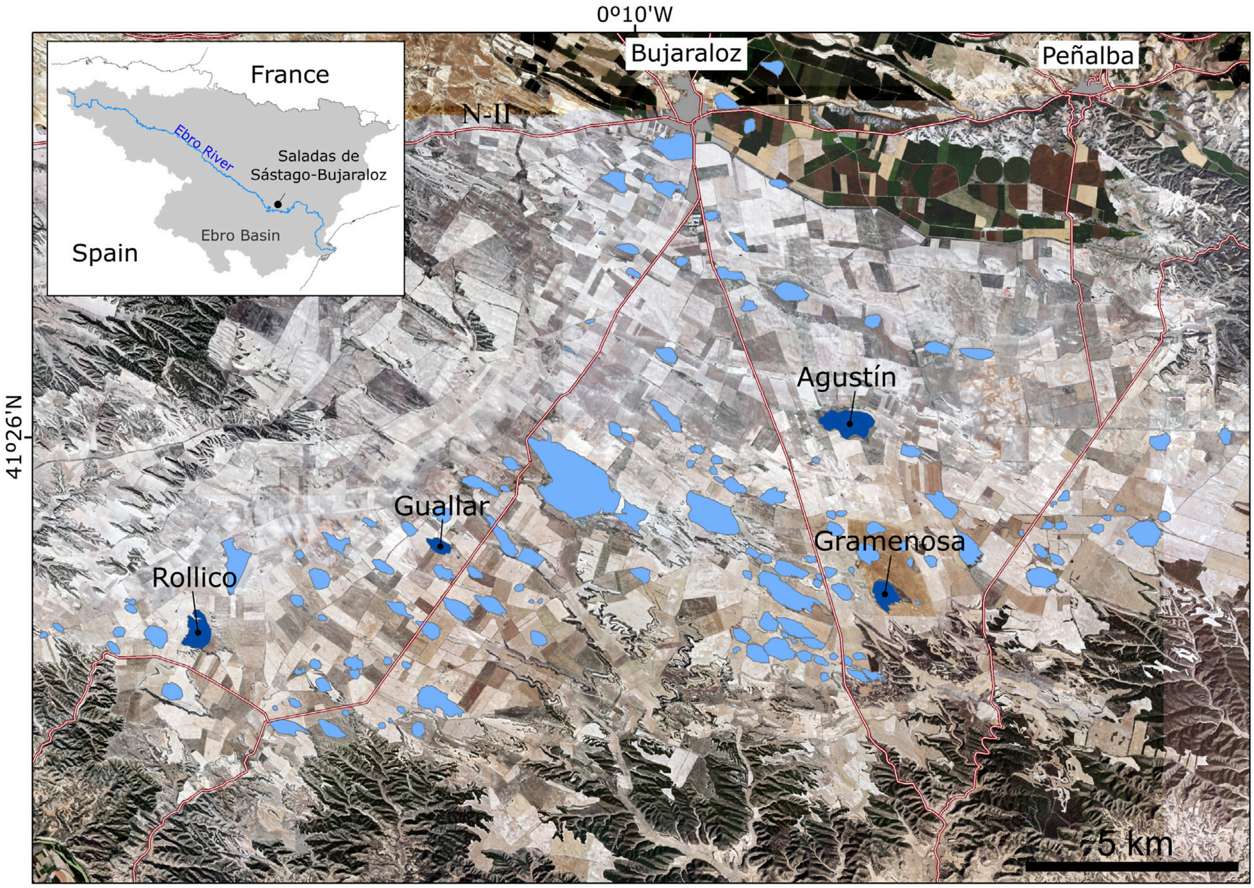

FIGURE 1 | Distribution of the saladas of Sástago-Bujaraloz in the dryfarmed area of Monegros, At the top of the PNOA background image, the irrigated area with the towns indicated. The four wetlands studied in this work are in dark blue and labelled.

activities, with minor impacts on the environment. In this scenario, the hypersaline wetlands—now protected by environmental legislation—were conserved. This is the case of our study area (**Figure 1**), the Monegros region located in the central Ebro Basin (CEB).

Over the last decades, Monegros has undergone radical transformations with strong impacts on its ecological functions affecting the survival of the saline enclaves (Pedrocchi and Sanz, 1991; Domínguez-Beisiegel et al., 2013a). These transformations include irrigation schemes both in operation and in progress, or intensive swine farms that are legally spreading slurry causing an excess of 441 t N in the basin (Tierra et al., 2025). Upcoming transformations include electricity production by solar panels and windmills, whose effects on near-surface wind speed, ground temperature and evaporation remain poorly known.

The Saladas of Sástago-Bujaraloz in Monegros are saline wetlands with alternating inundation and drying episodes and with a water salinity in some of their bottoms 10 times higher than that of the sea water. Their water regime, together with their chemical characteristics and semiarid climate (Herrero and Snyder, 1997), make possible a unique vegetation, unparalleled in Europe (Conesa et al., 2011; FAO, 2024). These closed depressions scattered in the landscape were surrounded by rainfed winter cereals—mainly barley (*Hordeum vulgare* L.)— as far as the topography and the soil salinity allow, and often with crops sowed even within the wetland depressions. Yields, controlled by the scarce and variable seasonal rainfall, are very irregular (McAneney and Arrúe, 1993; Castañeda and Moret-Fernández, 2013). The socioeconomic scenario was modified by European Union subsidies and the prospects of conversion to irrigation. Protected saline habitats are sensitive to land use changes at the wetland-crop interface and could be affected by agricultural actions, in some cases with the main objective of earning subsidies. The protection of saladas ought to consider the extent and variability of salinity not only in their bottoms, but also in surrounding agricultural soils.

Since the later 20th century, field assessment and mapping of a number of soil characteristics have become affordable in terms of cost and time thanks to the advent of portable electromagnetic sensor (EMS) (McNeill, 1991). Soil salinity appraisal using EMS is a well-established technique used in many countries (Corwin and Scudiero, 2019) including the CEB, e.g., Herrero and Pérez-Coveta (2005) or Casterad et al. (2018), illustrating how the

EMS-directed sampling reduces the number of soil samples needed.

The objective of this work is to implement edaphic salinity as a criterion to regulate agricultural activity by establishing limits for cultivation in the wetland-crop interface, without affecting the farmer's subsidies. With this purpose, we studied usefulness of the EMS in relation to the geomorphological setting in order to speed up the field survey and to reduce the number of soil samples needed.

STUDY AREA

A complex of almost 150 playa-lakes and closed depressions hosting temporary saline wetlands occurs in three conterminous municipalities, Sástago, Peñalba and Bujaraloz, located in the CEB (**Figure 1**). The Saladas of Sástago-Bujaraloz belong to the European Natura 2000 network of protected areas (ES2430082 and ES0000181) and to the Ramsar list of wetlands of international importance (Ramsar Convention Secretariat, 2010). These wetlands, with elevations ranging from 320 m to 417 m a.s.l., occupy depressions of karstic and aeolian origin developed on subhorizontal continental Tertiary limestones intercalated with gypsum and saliferous lutites (Salvany et al., 1996).

The climate is characterized by interannual and seasonal irregular scarce rains, high temperature fluctuations and a persistent NW dry wind. These factors result in high hydric deficit in the area. Daily data from the nearby Valfarta weather station (SIAR network[1]) give an annual mean precipitation of 358.8 mm, 1,261.7 mm of evapotranspiration (ET_0), and a temperature of 14.1 °C for the period 2004–2024. Despite the hydric deficit, most saline wetlands maintain a wet bottom and a sheet of water with variable persistence (Castañeda et al., 2005) due to the groundwater supply, which reach 40% of the total water input into the wetlands (Castañeda and García-Vera, 2008). Groundwater is highly saline reaching 175 dS m^{-1} (Paracuellos, 2006).

Soil development is conditioned by the climate and the lithology. The salinity of the soils is related to the saliferous lutites, main source of the groundwater salinity. The agricultural area surrounding the saladas has non-saline soils rich in carbonate and gypsum with low organic matter content (Castañeda et al., 2009). The saladas bottoms are extremely flat and are very saline with the formation of salt crust (Domínguez-Beisiegel et al., 2013b). Deep plowing with breakage of limestone and gypsum strata and their removal causes crop roots to gain access to saline materials (Cuchí, 1986).

Farmers have been demanding for decades the conversion of the area into irrigation. Several authors have indicated that this would lead to a rise in the shallow phreatic level due to the occurrence of perched groundwater levels and a low permeability of the geological materials (Cuchí, 1986; García-Vera, 1996; Castañeda, 2002). A decrease in arable land due to flooding and soil salinization can be expected. We selected four of the nearly 150 wetlands inventoried in the area by Castañeda et al. (2013) for study. The names of the selected saladas are Agustín, Gramenosa, Guallar and Rollico (**Figure 1**).

MATERIALS AND METHODS

Geomorphological Mapping

A detailed geomorphological map of the studied wetlands was made through stereoscopic photointerpretation of contacts at 1: 33000 scale of the aerial photographs of USAF-B flight (1956–1957). The photointerpretation was digitalized and georeferenced using the geographic information system ArcGIS© (v.10.8.2). The topography of the wetlands basins was analysed by using a digital elevation model (DEM) with a pixel of 2 m derived from LiDAR-PNOA-cob2 2015 CC-BY 4.0 (scne.es) with a density of 0.5 point per m^{-2}.

Soil Survey Strategy

Four of the largest saladas were selected as representative of the diverse wetland types recognized in the endorheic system (Castañeda et al., 2013): the playa lakes Rollico (40.8 ha) and Guallar (14.9 ha) with bare bottom, and the wet basins Gramenosa (29.9 ha) and Agustín (62.5 ha) with perennial halophytes and arable land. All them are affected by advancing plowing and cropping as the soil wetness allows the machinery to enter. Agustin occupies the bottom of a flat-bottomed valley with a relatively smooth topography and a higher agriculture imprint.

Two different methods were used for the soil salinity survey. A first campaign consisted in soil sampling along transects extending through the wetland-crop interface. The transects include the bottom (bare or vegetated), fringe of natural vegetation, and agricultural plots. According to the basin geomorphology, these transects were of NW-SE direction in Guallar and Rollico, and of NE-SW direction in Gramenosa (**Figures 2a–c**). The second soil sampling campaign was conducted in Agustin, in agricultural plots declared as "arable land" in the Land Parcel Identification System (LPIS), the information system recording all agricultural parcels in the EU Member States and key control mechanism under the Common Agricultural Policy (CAP) (European Court of Auditors, 2016). The accessible fringing area of the wetland was sampled with the EM sensor and three of these surveyed plots, named A1, A2, and A3, were selected for soil sampling (**Figure 2d**). **Table 1** summarizes the soil sampling characteristics. A total of 34 sites were sampled along the 1870 m of the three transects and 28 sites were distributed in three plots of Agustín over a total of 34.4 ha.

Field Sampling

Soil samples were extracted by using a 7 cm diameter Eijkelkamp hand auger at 20 or 25 cm intervals. At the different sites, the sampling depth and/or the depth intervals were not the same (**Table 1**) due to their different surveys or operators. The sampled depth of the soil ranged from 50 to 260 cm. A total of 183 soil samples were taken along the transects and 136 distributed in agricultural plots, totalizing 319 soil samples.

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[1] https://servicio.mapa.gob.es/websiar/

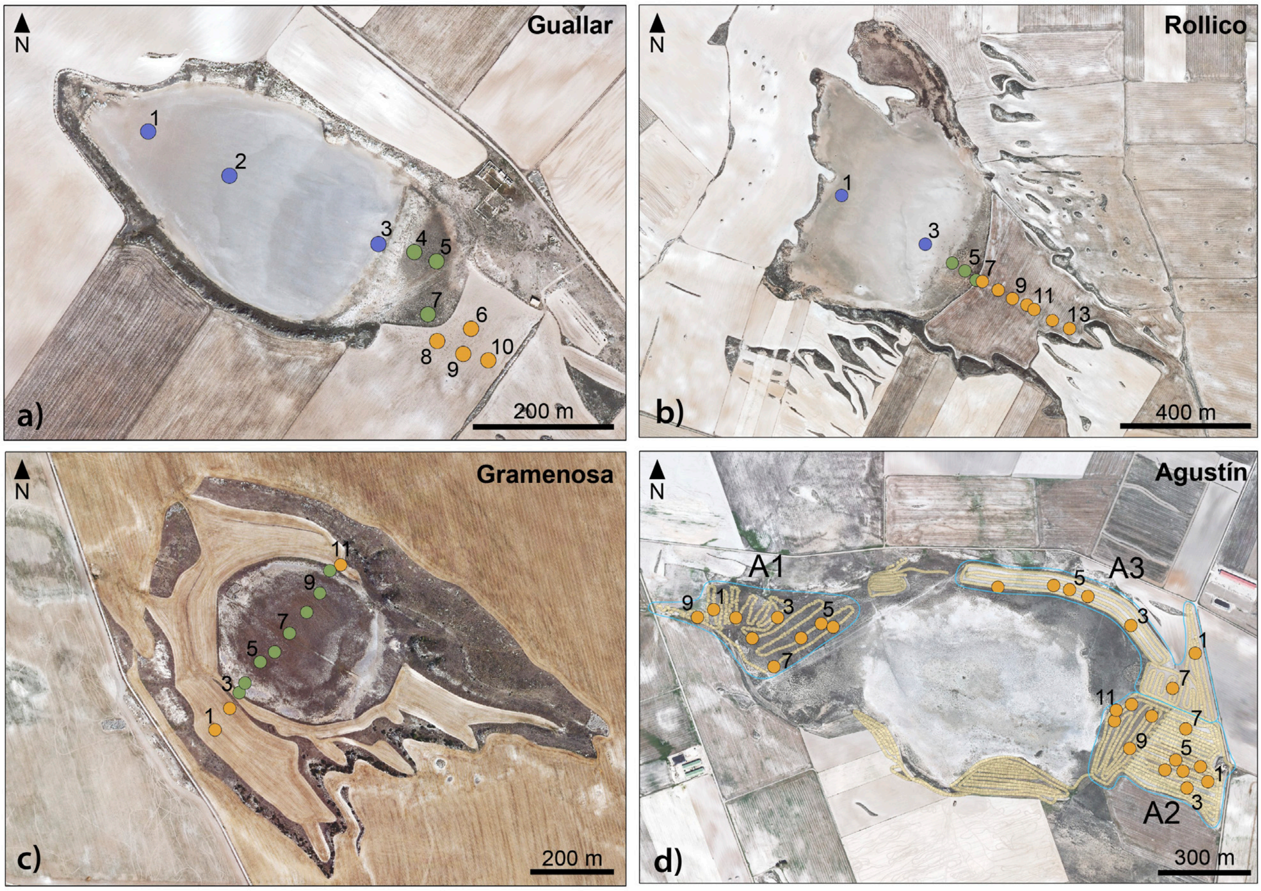

FIGURE 2 | Distribution of soil sampling sites in the transects along the interface wetland-crop in Guallar **(a)**, Rollico **(b)**, Gramenosa **(c)** and in the agricultural plots (A1, A2, A3) around Agustín **(d)**.

TABLE 1 | Soil sampling characteristics along transects and within plots.

Parameter described	**Wetland (salada) name**			
	Guallar	**Rollico**	**Gramenosa**	**Agustín**
Length of the sampled transect (m)	612.4	803.9	453.5	---
Surface area of the sampled plots (ha)	---	---	---	A1: 10.3 A2: 15.9 A3: 8.2
Maximum difference in elevation (m)	Bottom: 0.03 Fringe: 2.37	Bottom: 0.13 Fringe:8.09	Bottom: 0.26 Fringe: 4.67	A1: 2.42 A2: 1.81 A3: 2.55
Total number of sites sampled	10	13	11	A1: 9 A2: 12 A3: 7
Soil depth (cm) reached (*) min-max	Min 60 Max 260	Min 50 Max 125	Min 75 Max150	A1: Min 90 max 150 A2: Min 40 max 120 A3: All to 120
Soil sampling intervals (cm)	20	20 or 25	25	25
Total number of soil samples	66	50	67	136
Land cover/land use	Bare/Nat.veg./Dryfarmed	Bare/Nat.veg./Dryfarmed	Nat.veg/Dryfarmed	Dryfarmed
Groundwater depth (cm)	31–226	Flooded-71	131–148	Not accessed

(*) The soil depth (cm), minimum and maximum, reached with the hand auger in the points of the transect is illustrated in ***Figure 6****.*

We measured the groundwater depth and used a bailer-type sampler for taking water samples. Electrical conductivity (EC) and pH were determined in the field with the ORION 150A + conductivity meter and CRISON PH25 pH meter, respectively.

Electromagnetic Sensor Readings and Calibration

Electromagnetic sensor (EMS) readings were taken with a hand-held Geonics EM38 sensor in points along wetland-crop transects in Rollico, Guallar, and Gramenosa. The readings were taken 9 days after a rain of 32.2 mm in the nearby Valfarta weather station (SIAR network[2]), in trafficable soil conditions. The rainfall was enough for the correct operation of EMS. The readings were taken on the same day in horizontal and vertical positions of the sensor, i.e., coils parallel and perpendicular to ground, respectively. The readings were corrected with the conversion table of US Salinity Laboratory Staff (1954) in order to reference them to 25 °C. Then these dimensionless numbers (Herrero et al., 2024), divided by 100, were termed EMH and EMV, respectively. In Agustin we used the electromagnetic sensor DualEm 1S operating in horizontal (EMh) and vertical (EMv) positions. After Urdanoz and Aragüés (2012), this sensor gives measurements basically similar to EM-38. The Dualem sensor was mounted on a plastic sled towed by a tractor at a distance of 3 m allowing the automatic acquisition of georeferenced readings. The sensor was connected to a Garmin Etrex GPS and an Allegro CX computer (Juniper Systems, USA), where the sensor readings were recorded and georeferenced in real time. A preliminary map of mobile EMS readings was created in the field using the ArcGIS© kriging tool in order to decide the soil sampling points.

EMh y EMv were used for estimating soil salinity as ECe and EC1:5 at different sampled depth intervals using linear regression (López-Bruna and Herrero, 1996; Nogués et al., 2006) up to 100 cm. For the plots, the best regression equation of ECe was applied on the raster image produced with the DualEm 1S horizontal readings to generate the corresponding soil salinity map.

Laboratory Measurements and Data Analysis

Soil samples were dried at 30 °C–40 °C to avoid the loss of water from the gypsum ($CaSO_4 \bullet 2H_2O$) and grounded and sifted through a sieve of 2 mm mesh diameter. In all the soils we determined the electrical conductivity (EC) of 1:5 and 1:10 soil: water extracts with the conductivity meter Orion 013605MD. The pH was measured using a pH electrode (Orion 9157BNMD), and the major ions were determined by chromatography (Metrohm 861 Advanced compact IC, Metrohm AG, Herisau, Switzerland). The EC of the saturation extract (ECe) was determined in all the samples of the transects and in a half of the samples (69) of Agustin and it was estimated for the rest of Agustin samples using the regression of ECe on EC1:5.

The salinity profiles were analysed based on the EC1:5 extracts per sampling site using the original sampling depths. In order to compare the different sites, for each site we established a comparable depth up to 50 cm, as relevant for the cereal and vegetation roots activity, and to 100 cm to analyse possible influence of deeper layers or groundwater. The integrated salinity for these two depths was calculated by weighting the EC values by the thickness of each layer (Castañeda et al., 2012).

RESULTS

Landforms of the Saladas Previous to the Agricultural Intensification

The detailed geomorphological maps of the saline wetlands show a diversity of landforms, including lacustrine deposits associated with the flooded or vegetated bottoms and aeolian deposits on the leeward side of some of the saladas (**Figure 3**). The four studied saladas are inset into broader depressions usually framed by conspicuous flat-bottomed valleys excavated on the flat Miocene structural surface. The valleys network evidences structural and hydrological connection between neighboring depressions which stand out for their elongated shape in a NW-SE direction. Guallar (**Figure 3a**) develops along a NW-SE elongated depression with a major axis of about 1 km long and delimited to the northeast by a gypsum escarpment of about 10.4 m height that includes decimetric limestone strata. The flat bare lakebed extends to the aeolian deposit mainly covered by halophytes.

Rollico (**Figure 3b**) is inset within a relatively deep depression developed in the confluence of a wide structural surface developed to the NW and a pediment slope draining from the SW. The bare lakebed is enclosed by two lacustrine terraces, both of them less than 6 m high above the lake bottom, and by two adjacent aeolian deposits in the leeward zone. Gramenosa (**Figure 3c**) is part of a wider depression which includes a continuous colluvial deposit surrounding the main wetland and a small adjacent lakebed at the NW zone surrounded by vegetation. Agustin (**Figure 3d**) is located at the lowest topographic position of a complex area excavated into the largest flat-bottomed valley in the region, about 22 km long and 1.7 km of maximum width. The border of the depression hosting the wetland is blurred within the valley which includes a noticeable colluvium with a landslide to the north, together with small pediments. Leeward aeolian deposits are also present in the bottom of the depression.

The scarce elevation differences accounted along the transects (**Table 1**) provide evidence of the flatness of the saladas bottoms, especially in the bare soil of the playa lakes. A relatively higher topographic gradient is present along the vegetated fringe, varying from +2.4 m in Guallar to +8.1 m in Rollico. The fringe of Agustin around the vegetated bottom is relatively flat, with less than 2.5 m of elevation difference between the sampled sites.

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[2] https://servicio.mapa.gob.es/websiar/SeleccionParametrosMap.aspx?dst=1

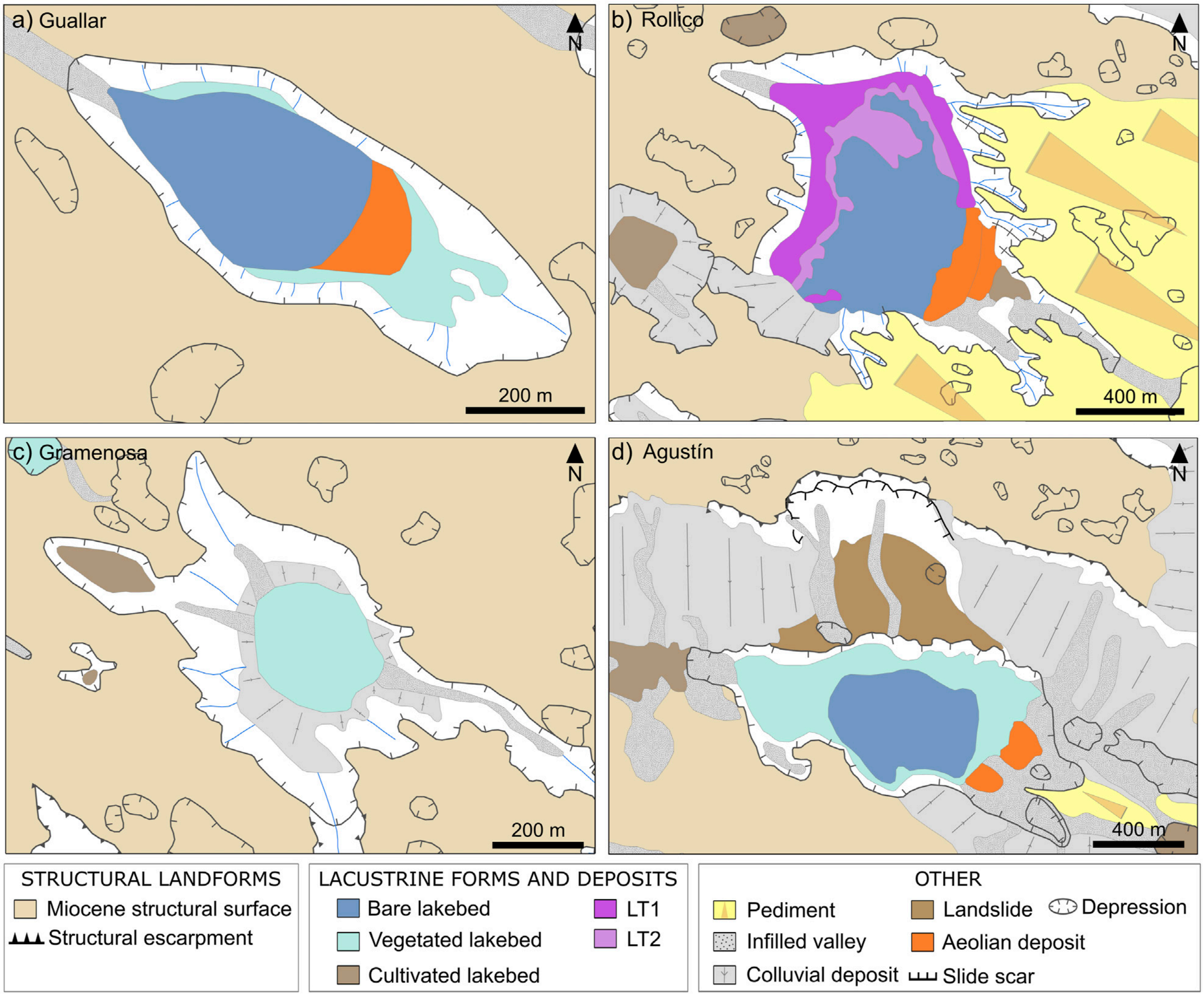

FIGURE 3 | Geomorphological maps of the studied saladas: Guallar **(a)**, Rollico **(b)**, Gramenosa **(c)** and Agustín **(d)**. Areas left in blank represent bear slopes where different substratum rocks outcrop (mainly gypsum and limestone).

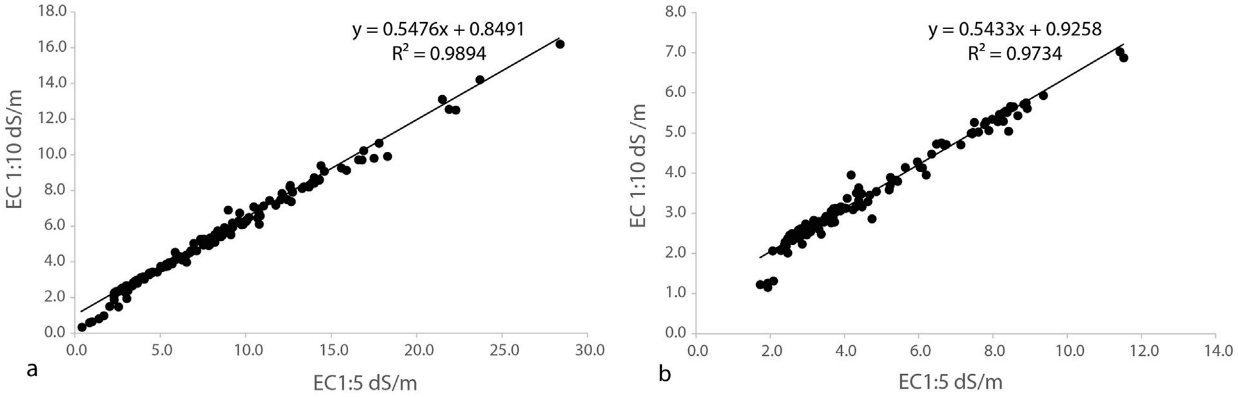

FIGURE 4 | Regression of CE1:10 on EC1:5 in the soil transects **(a)** and the plots **(b)**.

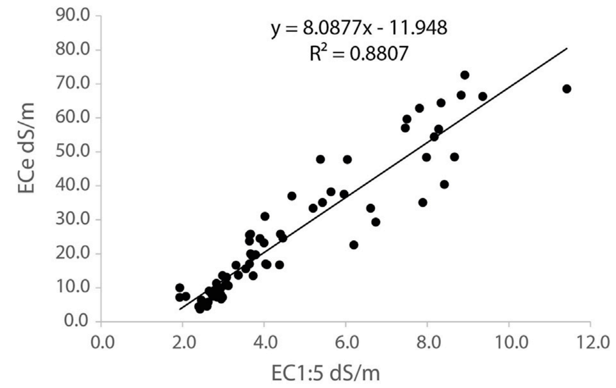

FIGURE 5 | Regression of ECe on EC1:5 of the 69 soil samples from Agustín having both determinations.

Assessment of the Electrical Conductivity

The regression of the EC1:5 versus EC 1:10 values obtained a $R^2 = 0.98$ in the transects and $R^2 = 0.97$ in Agustin plots. In both cases, the group of points more deviating are from line and near the origin of coordinates, corresponding to the low salinity values, less than 2.5 dS m^{-1}. A line can be fitted well (**Figure 4**) even without eliminating the points with lower EC, which probably show the presence of gypsum or maybe of more soluble salts in an insufficient proportion to reach the concentration of the 1:5 extract in the 1:10 extract.

In Agustin plots, the regression of ECe on CE1:5 for the 69 samples with both determinations gives a determination coefficient of 88% (**Figure 5**), and a standard error of 6.8 dS m^{-1} and allows to estimate the ECe for all the Agustin samples with **Equation 1**:

$$ECe = 8.0877\,x\,EC1:\,5 - 11.948 \qquad (1)$$

Spatial Distribution of Sol Salinity

Table 2 summarizes the soil salinity values for each salada as a whole and for each soil cover. The salinity shows a similar pattern in the three transects, in close relationship to the geomorphic position and the soil cover. The highest values occur in the bare soil bottom of the saladas (mean EC1:5 of about 15 dS m^{-1}), the intermediate values are found in the fringe of vegetation (from 6.5 to 10.2 dS m^{-1}), and the lowest values correspond to the soils of the crops (from 3 to 4.6 dS m^{-1}). Apart from the averaged values, there are also differences in the range of the EC values along the transect in each salada. The transects along Guallar and Rollico playa-lakes collect the highest salinity range (up to 27.7 dS m^{-1}) and a similar mean salinity at their bare bottom. The lowest mean salinity occurs in the vegetated saladas, Gramenosa and Agustin, with EC1:5 of 5.7 and 4.6 dS m^{-1}, respectively. Here the salinity range is about a third part of the range in the playa-lakes, about 9 dS m^{-1}.

The natural vegetation of Rollico fringe (**Table 2**) withstands higher salinity than that of Guallar or Gramenosa, not only by the mean but also the minimum EC values registered. The crops sampled along the transects exhibit also notable soil salinity, especially high in Agustin (mean 4.6 dS m^{-1}), followed by Guallar and Gramenosa, with 3.6 dS m^{-1} and 3.1 dS m^{-1}, respectively.

Based on the ECe salinity phases of Nogués et al. (2006), a 73% of the soil samples are very strongly saline (ECe >16 dS m^{-1}). They are spread in the saladas regardless of the soil cover, from the hypersaline bare soil of the playa-lakes to the crops. Similarly, most soil samples of the natural vegetation are very strongly saline. All the soil salinity phases, except the non saline, can be found in the cereal area: slightly (5%), moderately (14%), strongly (23%) and very strongly (58%) saline. Summarizing, half of the very strongly saline soils samples have been taken in agricultural areas with no soils free of salinity.

TABLE 2 | Main statistics of soil salinity determined in all the soil samples in the different soil covers of the wetlands.

Wetland (salada)	**EC1:5 (n = 319)**			**ECe (n = 319)**		
	Mean (±st dev)	**Max**	**Min**	**Mean (±st dev)**	**Max**	**Min**
All soil covers						
Guallar	9.6 (±5.5)	28.40	1.69	72.1 (±41.2)	139.0	6.2
Rollico	7.5 (±5.2)	21.90	2.29	53.4 (±45.7)	126.9	2.8
Gramenosa	5.7 (±2.4)	9.64	0.41	37.0 (±21.0	71.5	2.3
Agustin	4.6 (±2.2)	11.52	1.73	26.9 (±17.6)	77.0	3.7
Bare bottom						
Guallar	15.0 (±4.7)	28.40	9.58	116.7 (±12.9)	139.0	93.8
Rollico	15.4 (±3.0)	21.90	12.12	111.8 (±10.3)	126.9	93.5
Natural vegetation						
Guallar	7.6 (±1.5)	10.84	4.36	61.4 (±12.4)	78.9	33.2
Rollico	10.2 (±1.6)	12.72	7.35	88.9 (±13.4)	105.2	66.1
Gramenosa	6.5 (±1.8)	9.64	3.03	43.3 (±18.2)	71.5	8.6
Dryfarmed						
Guallar	3.6 (±0.8)	4.54	1.69	14.0 (±5.2)	21.5	6.2
Rollico	3.0 (±1.6)	4.03	2.29	10.7 (±7.7)	27.2	2.8
Gramenosa	3.1 (±2.0)	6.11	0.41	15.8 (±15.4)	38.7	2.3
Agustin	4.6 (±2.2)	11.52	1.73	26.9 (±17.6)	77.0	3.7

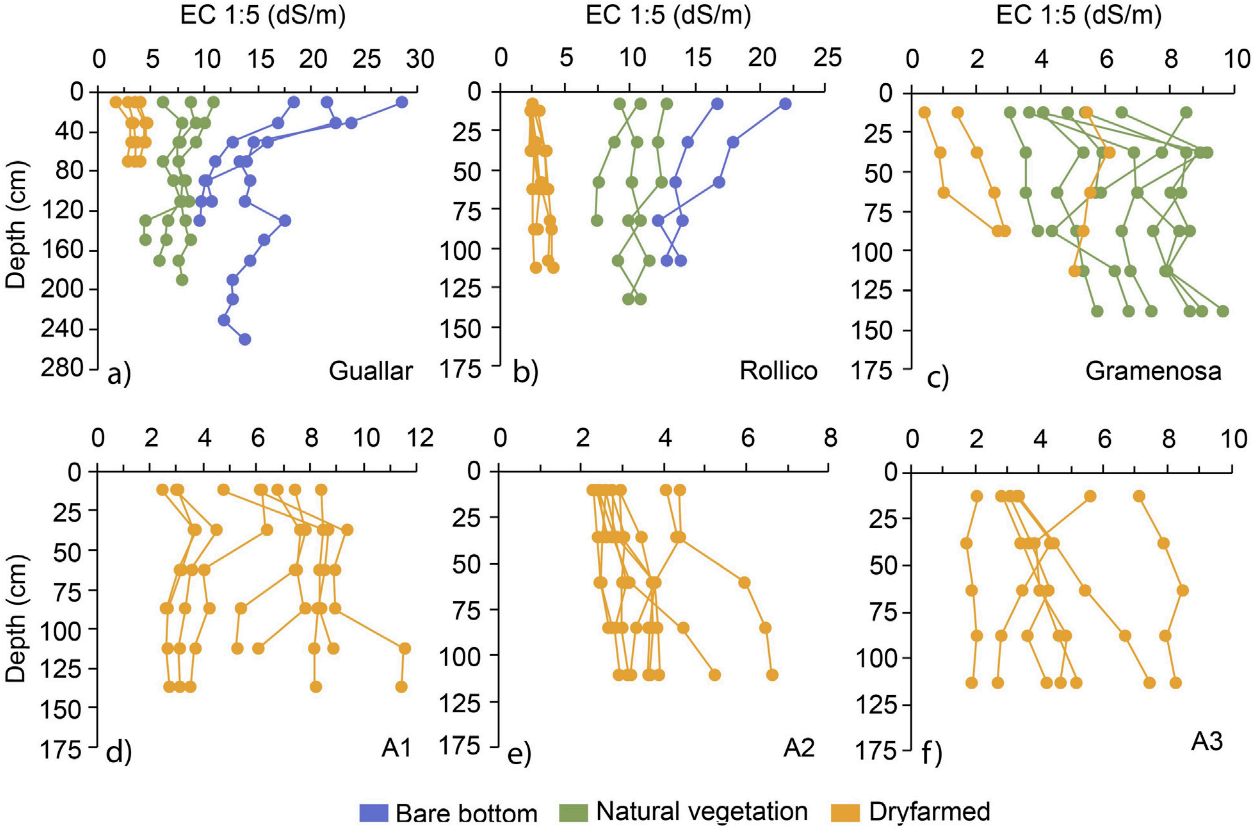

FIGURE 6 | EC1:5 profiles of soils sampled in Guallar **(a)**, Rollico **(b)**, Gramenosa **(c)**, and Agustín plots A1 **(d)**, A2 **(e)** and A3 **(f)**.

Vertical Distribution of Soil Salinity

Figure 6 illustrates the vertical distribution of soil salinity (EC1:5) within each salada, along the transects and in the dryfarmed area fringing Agustín. Salinity profiles were analyzed to depths ranging from 60 to 260 cm. The soil depth reached was very variable and, in general, lower at sites located on the crop area of the transects. At Guallar (**Figure 6a**) the sampled depth uniformly decreased towards the crops whereas at Rollico (**Figure 6b**) a similar depth was sampled in all the sites along the transect. There is a noticeable variability of the vertical distribution of soil salinity along the transects though in general, the salinity profiles can be grouped by soil cover, especially the upper soil horizons. Deeper horizons show a heterogeneous salinity pattern since the changes may occur at different depths. In general, the range of the soil salinity values along each transect is maximum at the surface horizons and clearly decreases with soil depth, especially in Guallar and Rollico.

The salinity profiles of Agustín reached up to 150 cm having a relatively uniform sampled depth (**Figures 6d–f**). The vertical distribution of salinity is heterogeneous even in the same plot and presents no relationship to the elevation. Unlike the transects, the range of salinity values are similar at the surface and subsurface horizons. The highest depth (150 cm) and the highest salinity range, EC1:5 from 2.5 to 11.5 dS m^{-1}, was reached at A1 plot (**Figure 6d**). The salinity can be maximum at the surface horizon, constant along the profile or can increase with depth. Frequently, a higher salinity ranging from 3.4 to 9.4 dS m^{-1} is observed in the first 50 cm. Only one point showed a considerable salinity increase deeper than 100 cm.

The saline profiles of A2 were quite uniform and represent a lower salinity range, from 2.3 to 6.6 dS m^{-1}, with only two sites with EC increasing with depth. All the A3 plot profiles were slightly shorter (up to 120 cm) and, similar to A1, showed a diversity of vertical salt distribution and the surface horizon (25 cm) can be very strongly saline, with EC1:5 up to 7.3 dS m^{-1}.

Salinity and Depth of the Groundwater

Groundwater was reached in some of the sampled sites along the transects (**Figure 7**), at depths ranging from 31 to 195 cm (before equilibrium) plus one site flooded in Rollico bottom. Once stabilize, the water level was at ~140 cm in sites #5 to #9 in the vegetated bottom of Gamenosa, with a mean EC of 82.6 dS m^{-1}; up to 25 cm at the bare bottom of Guallar (sites #1 to #3) and deeper (~190 cm) in the vegetated fringe (site #4), with 133 dS m^{-1} mean EC; and at ~70 cm in the bare bottom and vegetated fringe of Rollico (sites #1 to #6), with a mean EC of 144.3 dS m^{-1}. In general pH ranged from 6.8 to 7.3 and the anions composition was characterized by the high amount of chloride (54 g L^{-1}) followed by sulfate (27 g L^{-1}) with a ratio Cl/SO_4 of 2.7. The main

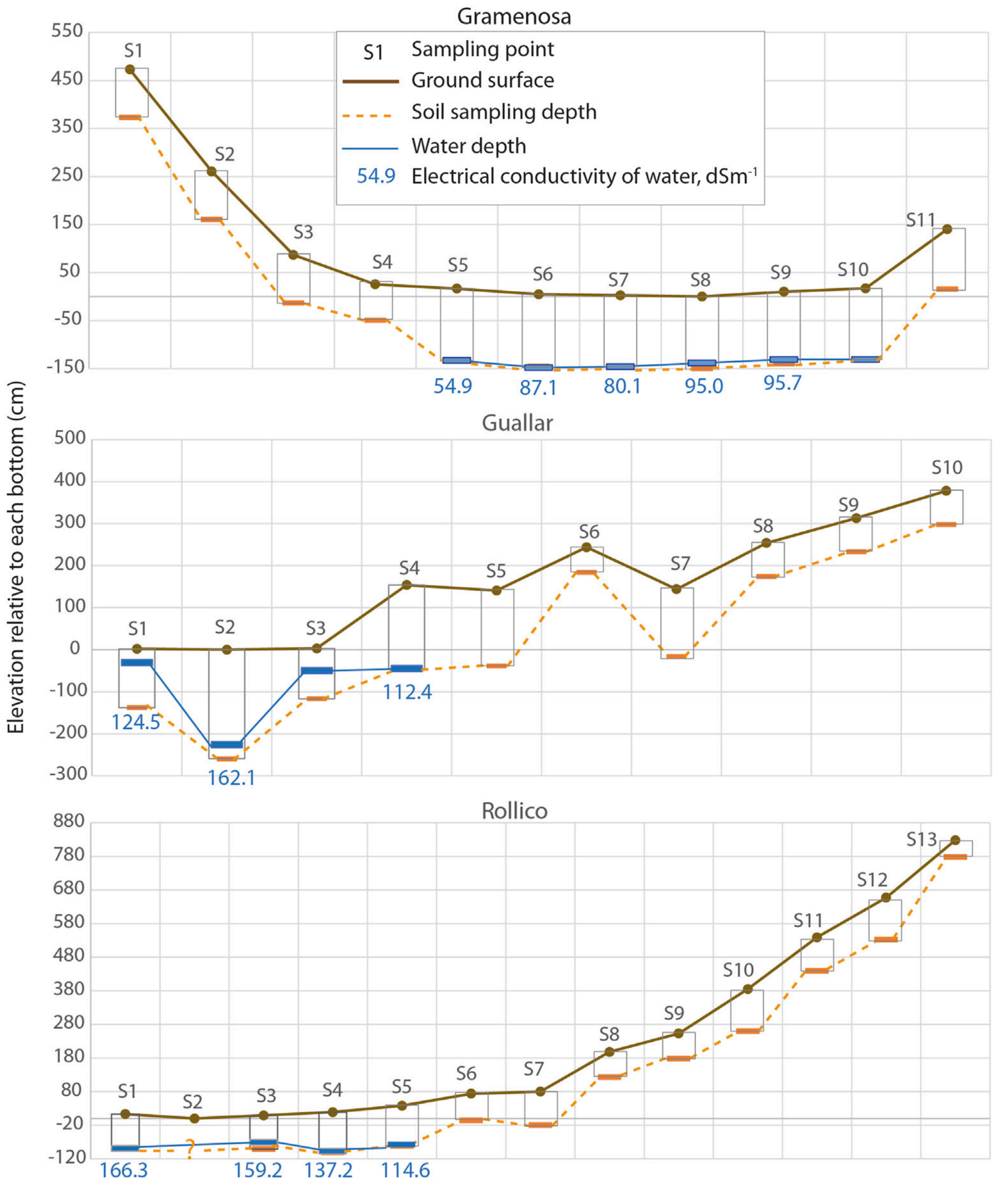

FIGURE 7 | The topographic profiles of Gramenosa, Guallar and Rolico saladas with the sampling points and soil depth reached. Where available, the water depth and its electrical conductivity are indicated. Horizontal axis not to scale, Figure 2 for reference.

cations were sodium (21 g L^{-1}) followed by magnesium (8 g L^{-1}) with a mean ratio Mg/Ca of 20.1.

Salinity Distribution in Integrated Soil Depths

Figure 8 summarizes the soil salinity of the saturation extract (ECe) weighted up to 50 cm (ECe50) and 100 cm (ECe100). The overall distribution of EC values at the sampled sites was consistent with the expected salinity. A limited number of sites can be classified as slightly or moderately saline. The salinity range along the transects showed some differences between both soil depths. In general, ECe100 was higher than ECe50, and the EC range of the vegetated saladas was not as wide as that of the playa-lakes. The ECe50 of the playa-lakes bottom can be twelve times that of the crops in Guallar and more than twenty times in Rollico. In these playa-lakes the ECe50 gradient was greater than that of ECe100 due to the high ECe50 values at their hypersaline bottom. The EC variability within Agustin plots can not be associated with systematic relevant topographic differences or the phreatic level.

The graphs of **Figure 8** show some local spots of unexpected high salinity, identified by the ECe of both depths. Most of these deviated points are located outside the salada bottom, in the leeward low-lying area of the aeolian deposits (orange in **Figure 3**) identified in Guallar

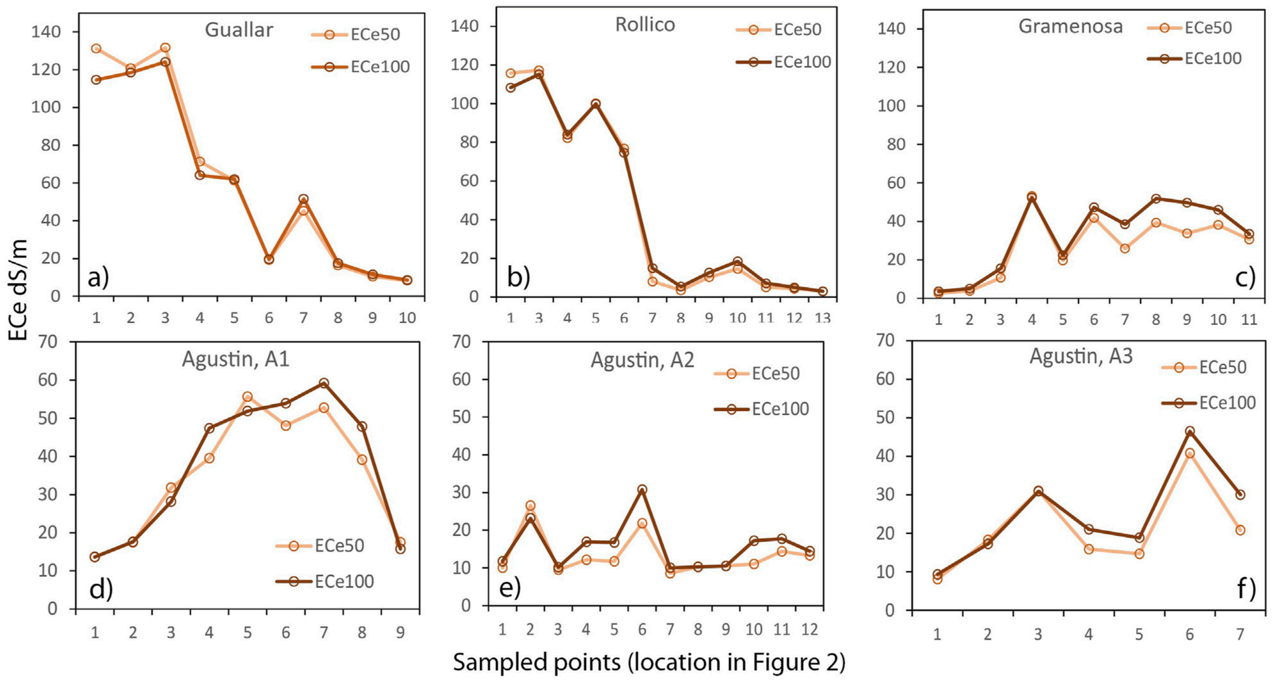

FIGURE 8 | Weighed soil salinity up to 50 cm (ECe50) and 100 cm (ECe100) of soil depth in the studied saladas: Guallar **(a)**, Rollico **(b)**, Gramenosa **(c)**, Agustin A1 **(d)**, Agustin A2 **(e)**, Agustín A3 **(f)**.

(**Figure 8a**, site #7), Rollico (**Figure 8b**, sites #9, #10), and Agustín A2 (**Figure 8e**, sites #4 to #6). A similar saline spot occurs on the edge at Gramenosa (site #4) (**Figure 2**). The water table was never reached at these sites during sampling or during the visits in the following 3 months.

Correlation Between EMS Readings and EC of Soil Extracts

The calibration of EMS to determine edaphic salinity in the studied transects, using the EC obtained from 1:5 and 1:10 soil extracts for integrated soil depths resulted in the equations summarized in Paracuellos (2006). The correlation analysis showed differences between the saladas (**Figure 9**). Only Rollico (**Figures 9b,e**) did not show differences in the coefficients of determination (R^2) between horizontal and vertical readings. At Gramenosa (**Figures 9c,f**), R^2 values were very low, the maximum being 4% in extract 1:5 at a depth of 0–20 cm. In both extracts, the regressions with EMh had higher determination coefficients than those with EMv for all depths. In 1:5 extract the best fit occurred up to the depth of 20 cm and became worse as depth increased, whereas in 1:10 extract the best fit occurred for the depth of 60 cm and thereafter R^2 decreased with soil depth. At Guallar (**Figures 9a,d**), R^2 values were acceptable for soil depths down to 80 cm (74%–87%), although there was a sharp decrease from this depth (45%–63%). The R^2 values were higher for settings with EMv (~81%) than with EMh (~69%). In Guallar the prediction EC1:5 values were established with the equation **Equation 2**,

$$EC1:\ 5 = 2.93 + 1.07 \times EMv \tag{2}$$

At Rollico (**Figures 9b,e**), for both extracts R^2 increased with depth even though the number of points that influence is smaller and the standard error is also smaller (Paracuellos, 2006). The maximum R^2 occurred at 100 cm, 94% and 96% at 1:5 and 1:10, respectively. R^2 was higher at all depths in the 1:10 extract. No significant differences in R^2 were observed in EMh and EMv.

For Guallar and Rollico the calibration equations corresponding to the 60 cm depth were appropriate because the salinity of this thickness was the most influential on cereal yield. They showed acceptable R^2, especially the 1:5 extracts (**Figures 9a,b**), whose values were 80% or higher. In Rollico, the calibration equation is **Equation 3**,

$$EC1:\ 5 = 2.53 + 0.63 \times EMh \tag{3}$$

The map of EMS readings (**Figure 10**) displayed a noticeable spatial variability within the Agustin plots. Higher R^2 values were obtained for the EMh than for EMv. The R^2 values were very low at the first layer (0–25), increasing from 0 to 50 cm. The correlation with EC1:5 was slightly better than with EC1:10. We selected the equation **Equation 4**,

$$ECe = 3.095 + 6.561 \times EMh \tag{4}$$

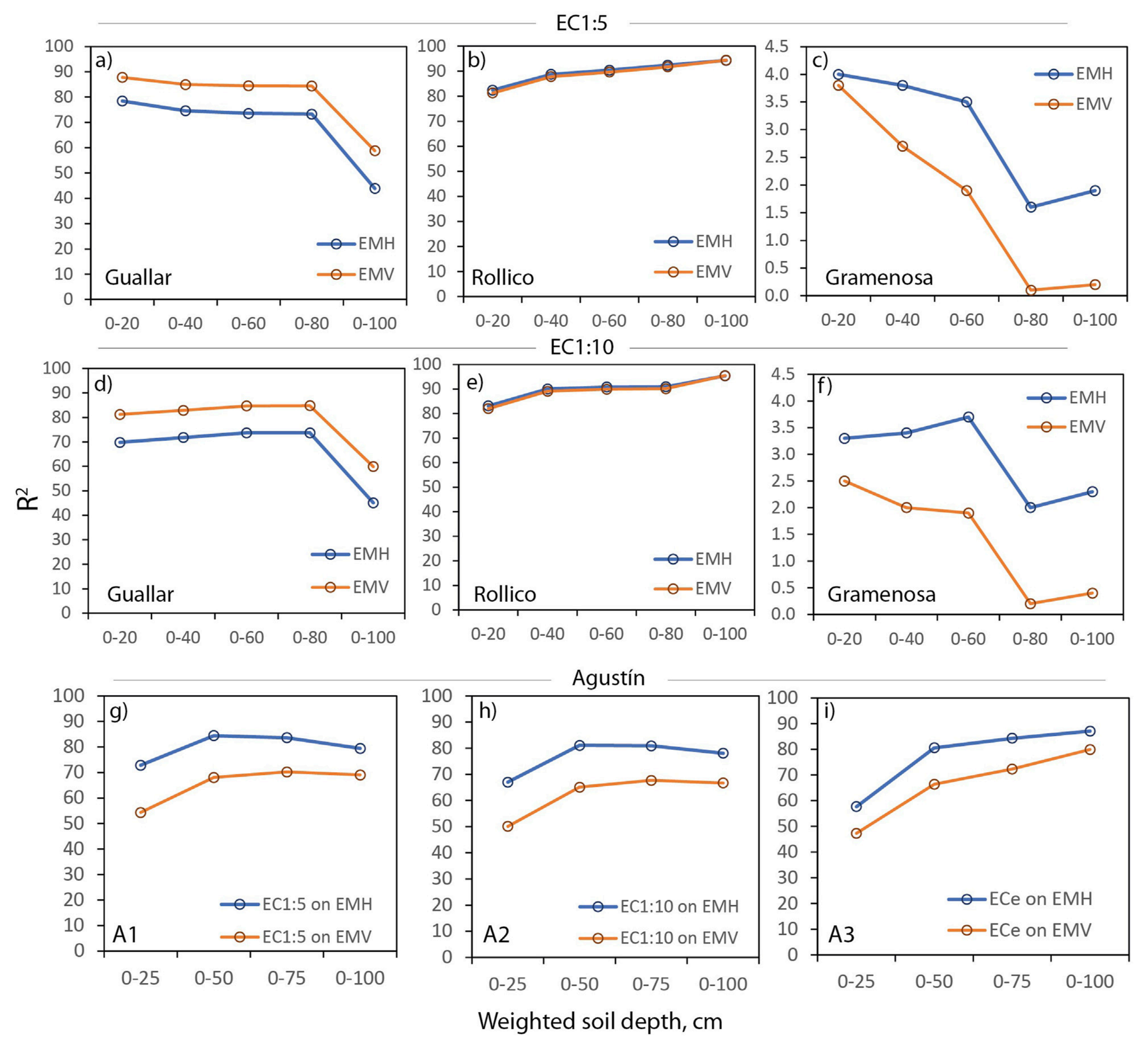

FIGURE 9 | Coefficients of determination (R^2) calculated for increasing soil depths. R^2 obtained from the lineal regressions of EMS readings on EC 1:5 and EC 1:10 in Guallar **(a,d)**, Rollico **(b,e)** and Gramenosa **(c,f)**, respectively. And R^2 obtained from ECe in Agustín A1 **(g)**, A2 **(h)** and A3 **(i)**.

with R^2 = 81%, corresponding to the weighted ECe up to 50 cm depth, the zone where most roots responsible for nutrient absorption under irrigation usually grow (Isla, 2001).

The resulting salinity map provided soil salinity estimation at unsampled sites (**Figure 11a**) and allowed for a comprehensive description of the salinity distribution and comparisons between the surveyed areas. Almost the complete fringe of Agustín depicted ECe >4 dS m^{-1}. The salinity decreased towards the crops in areas with higher elevation, especially in A2, because at higher topographic positions the depth of the water table increased. This area exhibited the greatest spatial variability of salinity from the studied plots. A concentric distribution was observed, with ECe >10 dS m^{-1} at the center and the rest of the area with values between 2 and 10 dS m^{-1}. The higher values occurred at the leeward depression of the aeolian deposit (**Figure 3d**) currently cultivated though with limited production (**Figure 11b**).

DISCUSSION

Soil salinity is well known as a threat in agricultural land (FAO, 2021) though the productive approach faces the occurrence of naturally saline soils even when they are unique and protected enclaves under international regulations (FAO, 2024). The

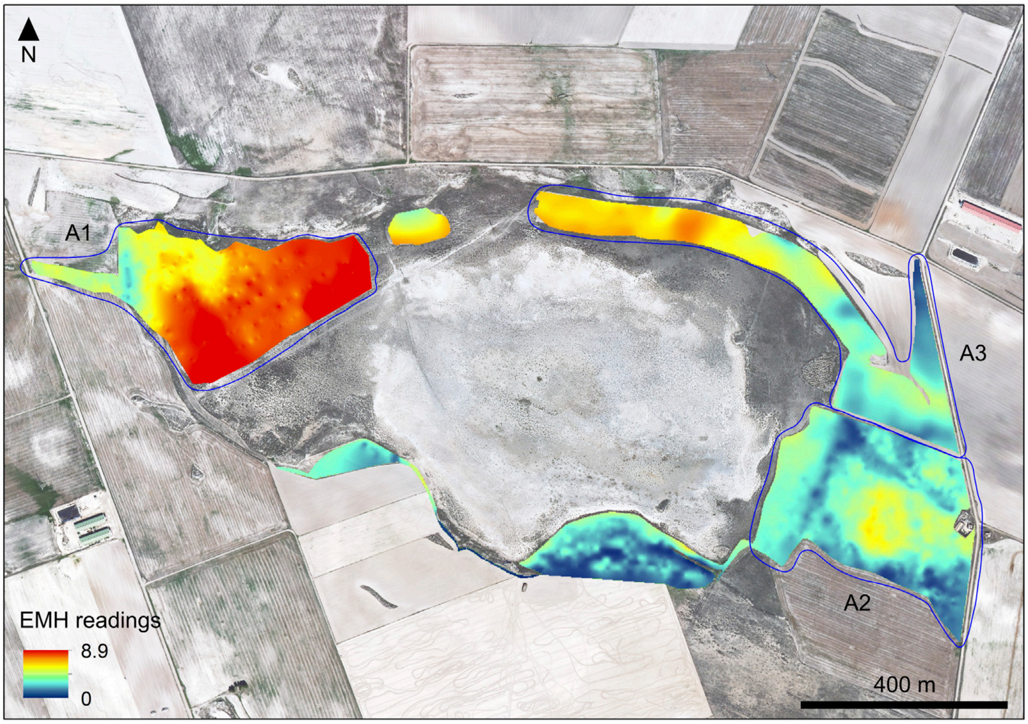

FIGURE 10 | Spatial variability of EMh values in the sampled plots around Agustin.

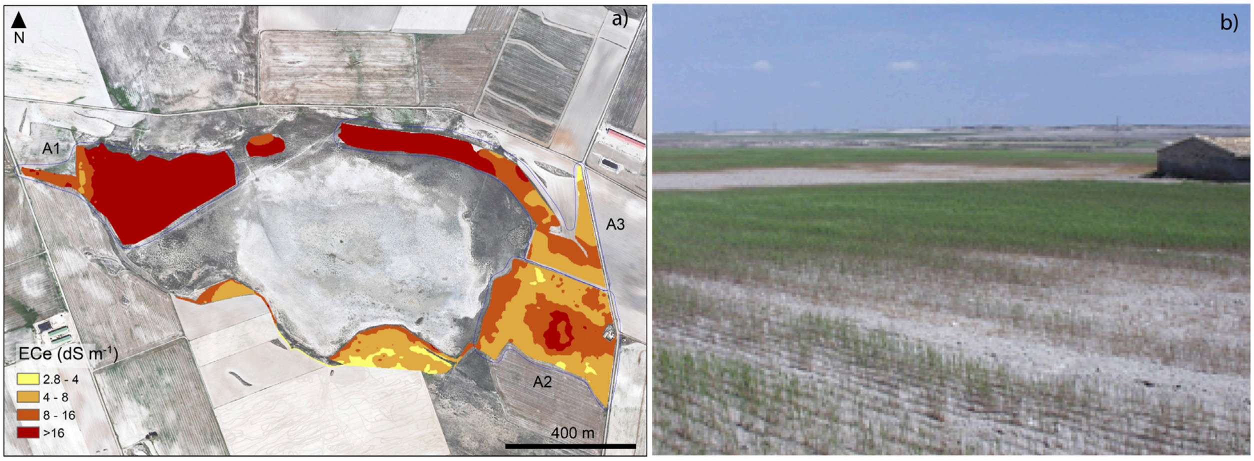

FIGURE 11 | **(a)** Salinity map (ECe) of the agricultural plots along the perimeter of the salada Agustín; **(b)** Field view the A2 plot in May 2008 showing in the foreground and background the limited growth of the wheat due to salinity.

saladas of Monegros are only an example of the co-occurrence of inland saline environments sharing conservation and production criteria.

The Agricultural Landscape

A diversity of landforms was identified in the saladas area, covering about 230 km^2, including halophytic vegetation in the saladas bottoms, aeolian deposits associated with bare playas, sharp escarpments, nested or coalescent depressions and networks of flat-bottomed valleys, among others. The detailed geomorphological map, based on the aerial photographs from 1957, captured the geoforms under landscape conditions previous to the homogenization produced by the transformations carried out to install the new irrigation (Domínguez-Beisiegel et al., 2013a).

A smoothed and homogeneous landscape was found during the soil surveys especially due to the land consolidation and excavation works for irrigation and drainage pipes. Following the disappearance of many of the saladas, the area now shows larger and more continuous agricultural fields free of vegetated fringes and with a great number of new intensive pig farms (Tierra et al., 2025). Under this scenario, the original mapped landforms (**Figure 3**) are key for interpreting the distribution of soil salinity and the frequent occurrence of superficial color patches with distinct soil properties (Castañeda and Moret-Fernández, 2013).

Similar transformations occurred in other semiarid environments in the CEB, such as the saladas of Alcañiz-Calanda, among others, and in other regions of Spain and saline environments worldwide usually requiring *in situ* knowledge to predict salinization effects and prevent degradation (Tedeschi, 2020).

Electrical Conductivity and Sampling Approaches

The EC of the saturation extracts is a worldwide accepted method established by the US Salinity Laboratory Staff (1954), originally aimed at agriculture for expressing soil salinity. We applied it in wetland ecosystems for meaningful comparisons in the continuum of habitats at the interface with agriculture. The EC determined in the two extracts, 1:5 and 1:10, are robust as showed by the relationships between them. The relationship between the ECe and EC1:5 is similar to that obtained by Herrero et al. (2015) computing 359 samples from 10 saladas not coincident with the ones studied in the present article. The regression result of ECe on EC1:5 in Agustín plots (R^2 = 88%) is comparable to that obtained for soils from the vegetated bottom of Agustín by Herrero (2008).

The response of EMS in Agustin presents the best relationship with a soil depth of 0–100 cm in A3 and with EMh readings (**Figure 9f**) although the relative contribution of the deep soil layers to the SEM readings is greater for the vertical position of the receiving coil (Abdu et al., 2007). These authors established a sensitive depth of exploration twice for vertical than for horizontal modes in a similar sensor. Yao and Yang (2010) proposed independent equations for each depth but Huang et al. (2015) considered that it is not necessary.

In Gramenosa, no acceptable fit was obtained, with low R^2 values. Despite this, the graphs obtained maintain a relationship in their form, and the regression equations show a certain consistency, indicating that the results could be more favorable if the number of observations increased. In Guallar, the fit was generally good, with R^2 values sharply dropping from 80 cm onward, possibly due to the smaller number of points or the influence of deeper layers. This is confirmed by the higher R^2 values in EMv, where the relative contribution of deeper layers is greater. Rollico provided a good fit for all depths and with great uniformity, even though the number of computed points decreased with depth.

The transect method is an appropriate approach to explore the soil salinity in the flat landscape of Monegros with scattered depressions. The inclusion of the gradients of salt-tolerant vegetation in the transects made it possible to capture a representative range of salinity. The resulting salinity range detected along the studied transects (from 9 to 26 dS m^{-1}) (**Figure 6**) can be used as a model to be extrapolated to all the area hosting about 150 depressions and halophytes (Conesa et al., 2011; Castañeda et al., 2013) with the help of digital mapping techniques together with soil salinity proxies (Zhang et al., 2011).

The geomorphological features, including topography, govern the movement and distribution of soil salinity as they condition how and where water flows accumulates. In this sense, the spatial distribution of salinity together with appropriate geomorphological maps (**Figure 3**) are very useful to predict the effects of irrigation and salt mobilization at the landscape scale (Duncan et al., 2008). On the other hand, the salinity maps based on calibrated mobile EMS readings are advantageous for continuous information of soil salinity, though the vehicle approach is restricted to accessible areas, e.g., agricultural plots or other semi-urban environments (Williams et al., 2024), not frequently found in natural areas.

Soil Salinity Variability at the Wetland-Crop Interface

The integrated salinity (**Figure 8**) allows comparing sites, soil covers, and saladas. The irregular soil salinity in relatively small agricultural plots (**Figures 8d–f**) with no relevant elevation differences could be related to the proximity of deeper saline layers even if no groundwater was reached on the sampling dates. García-Vera (1996) identified in Agustin the confluence of two aquifers in the area having dissimilar characteristics. Salvany et al. (1996) documented the frequent change of geological materials and groundwater characteristics at distances of few meters in the area, and the occurrence of local increases in salinity at the saladas fringe due to variable-density effects of groundwater. Besides, a great number of tectonic joints and the occurrence of preferential flows probably contributes to the heterogeneity of the subsurface materials yielding differences in soil salinity at distances of just a few meters.

Regarding the salinity profiles of **Figure 6**, one of the differences between the playa lakes and the agricultural plots is the striking high salinity range of the upper horizons in natural areas. The high ET_0 favors the capillary rise and evaporation through the bare soil (Castañeda and García-Vera, 2008) and subsequent salt accumulation in the upper layers, generating hypersaline areas that intensify the salinity gradient. On the contrary, the agricultural practices in the plots of Agustin very probably have a homogenizing effect on the upper layers of the soil profile (Ohigashi et al., 2025). To comply with CAP measures, continuous tillage is required under rainfed, even under long fallow practices (16–18 months).

Low values of Gramenosa may depend on the points chosen. Irregular salinity values in vegetated areas may be related to the higher density of the vegetation cover and the abundance of nitrophilous plants interspersed with the salinity-driven plant succession. Under these conditions, the soil cover changes cannot be precisely distinguished when selecting sampling sites. Sampling more closely aligned with lateral variation in soil salinity would require a prior study of plant distribution at a very detailed scale.

The salinity intervals for soil salinity classes (Nogués et al., 2006) were designed for agricultural soils and leave the samples with

ECe >16 dS m^{-1} in a single group, that is, 73% of the 319 samples studied. Regarding these intervals, new considerations would be needed to integrate the agricultural and ecological perspectives into the study of soil salinity in hypersaline areas.

The Agronomic Perspective

The surface extent affected by salinity of **Figure 11a** can be quantified for individual CAP parcels of the interface between crops and the protected habitats. For agronomic application, a production criterion could be applied to establish a reference limit of production for each parcel (Serrate, 2009). As an example, Royo and Abió (2003) established as criterion a 50% decrease in durum wheat and barley yield due to the presence of salts in the soil. The authors obtained a mean salinity value (EC50) of 11.3 dS m^{-1} as a limiting factor. EC50 is the electrical conductivity of saturation extract, which reduces yield to half of what would be obtained under non-saline soil conditions. This value would be more restrictive than that of barley, which can tolerate much higher salinity levels, with EC50 = 18 dS m^{-1} (Ayers and Westcott, 1985). In this context, a proposal for a new agri-environment-climate measure could include qualifying plots with ECe >10 dS m^{-1} in more than 50% of the surface area. These plots could be considered not suitable for cultivation such as that of **Figure 10b**.

Some of the CAP greening obligations are to be monitored using the Land Parcels System (LPIS). Since part of the CAP subsidies to farmers are to be paid for agricultural practices beneficial for the climate and environment (e.g., benefit biodiversity, habitat restoration and maintenance, or retain landscape features), the plots of limited agricultural potential may form part of a new category of eligible areas within the LPIS as non-productive areas prone to natural variable salinity as proposed by Serrate (2009). Moreover, as recommended by European Court of Auditors (European Court of Auditors, 2016) to accurately identify this type of land as eligible, targeted on-the-spot data may be required, and this requirement is well suited for soil salinity due to their intrinsic temporal variability.

CONCLUSION

This study carried out in the Saladas of Sástago-Bujaraloz presents an approach applicable to semiarid agricultural areas within Natura 2000 sites. All the surveyed soils, including bare, vegetated, fallow or cultivated, are saline, with EC ranging from slightly to very strongly saline. The results obtained about the spatial and vertical distribution of soil salinity show the complexity of the area, paralleling the hydrological complexity documented by previous studies. There is a highly variable salinity within a few metres of distance, especially in the plots of Agustín declared as eligible under LPIS. Guallar, Rollico and Gramenosa show a similar salinity pattern along the transects, and also include eligible very saline plots.

Both manual sampling along topographic transects and EMS readings across flat areas are suitable methodologies for use on this and similar environments with limiting conditions for production. The calibrated salinity maps provide a more complete view of soil salinity in order to quantitatively delimit non-productive areas in the context of CAP regulations. A proposal for a new agri-environment-climate measure could include classifying plots with ECe >10 dS m^{-1} in more than 50% of the area as unsuitable for cultivation.

A diversity of landscape forms and associated processes were identified and mapped despite the general flatness of the area. The landscape features control the water flows and the accumulation of salts in the soil and subsoil, and the next fresh water inputs under new irrigation schemes will increase this potential. The characterization of landforms may allow for a qualitative estimation of new areas prone to salinization under irrigation. Future investigations should include appropriate water flow models for a better understanding of salinity distribution and irrigation effects. This knowledge may help in mitigating salt mobilization and preventing the salinization of productive areas.

DATA AVAILABILITY STATEMENT

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

AUTHOR CONTRIBUTIONS

MT, CC, and FJ participated in the design, interpretation of the studies and analysis of the data and ETM performed the data curation and organization. MT, CC, and FJG participated on the review of the manuscript; CC managed the project administration and funding acquisition. All authors contributed to the article and approved the submitted version.

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CONFLICT OF INTEREST

The authors(s) declared that this work was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

GENERATIVE AI STATEMENT

The author(s) declared that generative AI was not used in the creation of this manuscript.

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REFERENCES

Abdu, H., Robinson, D. A., and Jones, S. B. (2007). Comparing Bulk Soil Electrical Conductivity Determination Using the DUALEM-1S and EM38-DD Electromagnetic Induction Instruments. *Soil Sci. Soc. Am. J.* 71 (1), 189–196. doi:10.2136/sssaj2005.0394

Ayers, R. S., and Westcott, D. W. (1985). “Water Quality for Agriculture,” in *FAO Irrigation and Drainage Paper No.29*. Rome: FAO. Available online at: https://www.fao.org/4/t0234e/t0234e00.htm.

Castañeda, C. (2002). El Agua De Las Saladas De Monegros Sur Estudiada Con Datos De Campo Y De Satélite. *Cons. Protección la Nat. Aragón* 35, 158. Available online at: http://hdl.handle.net/10261/399164

Castañeda, C., and García Vera, M. A. (2008). Water Balance in the Playa-Lakes of an Arid Environment, Monegros, NE Spain. *Hydrogeology J.* 16, 87–102. doi:10.1007/s10040-007-0230-9

Castañeda, C., Herrero, J., and Casterad, M. A. (2005). Landsat monitoring of playa-lakes in the Spanish Monegros Desert. *J. Arid Environ.* 63, 497–516. doi:10.1016/j.jaridenv.2005.03.021

Castañeda, C., and Moret-Fernández, D. (2013). Superficial Color Patches as a Visual Diagnostic Criterion for Agricultural Management. *Pedosphere* 23 (6), 740–751. doi:10.1016/s1002-0160(13)60066-1

Castañeda, C., Mendez, S., Herrero, J., and Betrán, J. (2009). “Investigating Soils for Agri-Environmental Protection in Arid Spain,” in *Land Degradation and Desertification: Assessment, Mitigation and Remediation*. Editor P. Zdruli (Springer–Verlag). doi:10.1007/978-90-481-8657-0_41

Castañeda, C., Latorre, B., and Herrero, J. (2012). SLICES Versión 2.0; Synthetic Layers of Soil. doi:10.20350/digitalCSIC/9000

Castañeda, C., Herrero, J., and Conesa, J. A. (2013). Distribution, Morphology and Habitats of Saline Wetlands: A Case Study from Monegros. *Geol. Acta* 11 (4), 371–388. doi:10.1344/105.000002055

Casterad, M. A., Herrero, J., Betrán, J. A., and Ritchie, G. (2018). Sensor-Based Assessment of Soil Salinity During the First Years of Transition from Flood to Sprinkler Irrigation. *Sensors* 18 (2), 616. doi:10.3390/s18020616

Conesa, J. A., Castañeda, C., and Pedrol, J. (2011). “Las Saladas De Monegros Y Su Entorno: Hábitats Y Paisaje Vegetal,” in *Consejo De Protección De La Naturaleza De Aragón*. Zaragoza, 540. Available online at: http://hdl.handle.net/10261/109666.

Corwin, D. L., and Scudiero, E. (2019). Review of Soil Salinity Assessment for Agriculture Across Multiple Scales Using Proximal And/Or Remote Sensors. *Adv. Agron.* 158, 1–130. doi:10.1016/bs.agron.2019.07.001

Cuchí, J. A. (1986). *Aportaciones al conocimiento de los suelos salinos de Aragón*. Zaragoza: Estación Experimental de Aula Dei (EEAD-CSIC). Available online at: http://hdl.handle.net/10261/184404.

Domínguez-Beisiegel, M., Herrero, J., and Castañeda, C. (2013a). Saline Wetlands Fate in Inland Deserts: An Example of Eighty Years Decline From Monegros, Spain. *Land Degrad. & Dev.* 24 (3), 250–265. doi:10.1002/ldr.1122

Domínguez-Beisiegel, M., Castañeda, C., and Herrero, J. (2013b). Two Microenvironments at the Soil Surface of Saline Wetlands in Monegros, Spain. *Soil Sci. Soc. Am. J.* 77 (2), 653–663. doi:10.2136/sssaj12.0014

Duncan, R. A., Bethune, M. G., Thayalakumaran, T., Christen, E. W., and McMahon, T. A. (2008). Management of Salt Mobilisation in the Irrigated Landscape – A Review of Selected Irrigation Regions. *J. Hydrology* 351, 238–252. doi:10.1016/j.jhydrol.2007.12.002

European Court of Auditors (2016). *The Land Parcel Identification System: a useful tool to determine the eligibility of agricultural land - but its management could be further improved (Special Report 25/2016)*. Luxembourg: Publications Office of the European Union. Available online at: https://www.eca.europa.eu/lists/ecadocuments/sr16_25/sr_lpis_en.pdf.

FAO (2021). *Global Map of Salt-Affected Soils Gsasmap v1.0*. Rome, Italy: FAO, 20. Available online at: https://www.fao.org/documents/card/en/c/cb7247en.

FAO (2024). Global Status of Salt-Affected Soils. *Main. Report*. doi:10.4060/cd3044en

García-Vera, M. A. (1996). Hidrogeología De Zonas Endorreicas En Climas Semiáridos: Aplicación a Los Monegros (Zaragoza Y Huesca). *Cons. Protección la Nat. Aragón* 3, 297.

Herrero, J. (2008). Salinidad Edáfica En Varios Salobrares De Aragón. Memorias De La Real Sociedad Española De Historia Natural. *Tomo* IV, 177. Available online at: http://hdl.handle.net/10261/61398.

Herrero, J., and Pérez-Coveta, O. (2005). Soil Salinity Changes over 24 Years in a Mediterranean Irrigated District. *Geoderma* 125 (3-4), 287–308. doi:10.1016/j.geoderma.2004.09.004

Herrero, J., and Snyder, R. L. (1997). Aridity and Irrigation in Aragon, Spain. *J. Arid Environ.* 35, 535–547. doi:10.1006/jare.1996.0222

Herrero, J., Artieda, O., and Hudnall, W. H. (2009). Gypsum, a Tricky Material. *Soil Sci. Soc. Am. J.* 73 (6), 1757–1763. doi:10.2136/sssaj2008.0224

Herrero, J., Weindorf, D. C., and Castañeda, C. (2015). Two Fixed Ratio Dilutions for Soil Salinity Monitoring in Hypersaline Wetlands. *PLoS ONE* 10 (5), e0126493. doi:10.1371/journal.pone.0126493

Herrero, J., López-Bruna, D., and Predebon, I. (2024). What Do Electromagnetic Sensors Measure in Soil Surveys? *Adv. Agron.* 187, 1–19. doi:10.1016/bs.agron.2024.05.001

Huang, J., Mokhtari, A. R., Cohen, D. R., Monteiro-Santos, F. A., and Triantafilis, J. (2015). Modelling Soil Salinity Across a Gilgai Landscape by Inversion of EM38 and EM31 Data. *Eur. J. Soil Sci.* 66 (5), 951–960. doi:10.1111/ejss.12278

Isla, R. (2001). *Efecto De La Salinidad Sobre La Cebada (Hordeum Vulgare L.). Análisis De Caracteres morfo-fisiológicos Y Su Relación Con La Tolerancia a La Salinidad*. Tesis doctoral. Lleida, Spain: Universidad de Lleida, 100. Available online at: http://hdl.handle.net/10803/8324.

López-Bruna, D., and Herrero, J. (1996). El Comportamiento Del Sensor Electromagnético Y Su Calibración Frente a La Salinidad Edáfica. *Agronomie* 16, 95–105. doi:10.1051/agro:19960203

McAneney, M. C., and Arrúe, J. L. (1993). A wheat-fallow Rotation in Northeastern Spain: Water balance-yield Considerations. *Agronomie* 13 (6), 481–490. doi:10.1051/agro:19930604

McNeill, J. D. (1991). Advances in Electromagnetic Methods for Groundwater Studies. *Geoexploration* 27 (1–2), 65–80. doi:10.1016/0016-7142(91)90015-5

Nogués, J., Robinson, D. A., and Herrero, J. (2006). Incorporating Electromagnetic Induction Methods into Regional Soil Salinity Survey of Irrigation Districts. *Soil Sci. Soc. Am. J.* 70, 2075–2085. doi:10.2136/sssaj2005.0405

Ohigashi, T., Madegwa, Y. M., Karuku, G. N., Njira, K., Uchida, Y. (2025). Agricultural land use induces broader homogenization of soil microbial functional composition than taxonomic composition in sub-Saharan Africa. *Soil Biol. Biochem.* 209, 109895. doi:10.1016/j.soilbio.2025.109895

Paracuellos, E. (2006). Medida Y Evaluación De La Salinidad Edáfica En Monegros Para Modulación De Las Ayudas De La PAC Por Superficies. Available online at: http://hdl.handle.net/10261/372938.

Pedrocchi, C., and Sanz, M. A. (1991). El Sistema Endorreico De Monegros: Un Ecosistema En Vías De Extinción. *Lucas Mallada* 3, 93–106. Available online at: https://revistas.iea.es/index.php/LUMALL/article/download/940/937.

Ramsar Convention Secretariat (2010). *Ramsar Handbooks for the Wise Use of Wetlands*. 1. Gland (Switzerland): Ramsar Convention Secretariat, 56.

Rhoades, J. D., and Corwin, D. L. (1981). Determining Soil Electrical-Conductivity Depth Relations Using an Inductive Electromagnetic Soil Conductivity Meter. *Soil Sci. Soc. Am. J.* 45 (2), 255–260. doi:10.2136/sssaj1981.03615995004500020006x

Royo, A., and Abió, D. (2003). Salt Tolerance in Durum Wheat Cultivars. *Span. J. Agric. Res.* 1 (3), 27–35. doi:10.5424/sjar/2003013-32

Salvany, J. M., García-Vera, M. A., and Samper, J. (1996). Geología E Hidrogeología De La Zona Endorreica De Bujaraloz-Sástago (Los Monegros, Provincias De Zaragoza Y Huesca). *Acta Geol. Hisp.* 30 (4), 31–50. Available online at: https://revistes.ub.edu/index.php/ActaGeologica/article/view/4578.

Serrate, L. (2009). *Estudio De Rasgos Edáficos Para Plantear Una Nueva Medida Agroambiental En Monegros Sur*. Spain: Universidad de Zaragoza. Available online at: http://hdl.handle.net/10261/172060.

Tedeschi, A. (2020). Irrigated Agriculture on Saline Soils: A Perspective. *Agronomy* 10, 1630. doi:10.3390/agronomy10111630

Tierra, M., Olarieta, J. R., and Castañeda, C. (2025). An Assessment of the N Load from Animal Farms in Saline Wetland Catchments in the Ebro Basin, NE Spain. *Land* 14 (6), 1170. doi:10.3390/land14061170

Tóth, G., Adhikari, K., Várallyay, G., Tóth, T., Bódis, K., and Stolbovoy, V. (2008). "Updated Map of Salt Affected Soils in the European Union," in *Threats to Soil Quality in Europe (EUR 23438, Issue May)*. Editors G. Tóth, L. Montanarella, and E. Rusco (Ispra, Italy: Office for Official Publications of the European Communities). doi:10.2788/8647

Urdanoz, V., and Aragüés, R. (2012). Comparison of Geonics EM38 and Dualem 1S Electromagnetic Induction Sensors for the Measurement of Salinity and Other Soil Properties. *Soil Use Manag.* 22 (1), 108–112. doi:10.1111/j.1475-2743.2011.00386.x

US Salinity Laboratory Staff (1954). Diagnosis and Improvement of Saline and Alkali Soils. *Agric. Handb.* 60. Available online at: https://www.ars.usda.gov/ARSUserFiles/20361500/hb60_pdf/hb60complete.pdf.

Williams, D. M., Straw, C. M., Smith, A. P., Watkins, K. L., Hong, S. G., Floyd, W. F., et al. (2024). Using Electromagnetic Induction to Inform Precision Turfgrass Management Strategies in Sand-Capped Golf Course Fairways. *Agrosyst. Geosci. Environ.* 7, e70020. doi:10.1002/agg2.70020

Yao, R., and Yang, J. (2010). Quantitative Evaluation of Soil Salinity and Its Spatial Distribution Using Electromagnetic Induction Method. *Agric. Water Manag.* 97, 1961–1970. doi:10.1016/j.agwat.2010.02.001

Zhang, T. T., Zeng, S. H., Gao, Y., Ouyang, Z. T., Chang-Ming Fang, B. L., Zhao, B., et al. (2011). Using Hyperspectral Vegetation Indices as a Proxy to Monitor Soil Salinity. *Ecol. Indic.* 11, 1552–1562. doi:10.1016/j.ecolind.2011.03.025

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Effect of Different Tree Plantations on the Chemical Properties and Microbial Activity in Galician Forests Soils

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Forest soils are crucial carbon sinks, with the soil microbial community playing a key role in the stabilization of organic matter and harboring numerous ecosystems services. These ecosystems can be affected, among other factors, by the different tree species present in the forest canopy. This study is focused on forests soils located in Galicia (on the north-west of Spain). Different soil properties and microbial activity were analyzed in 54 forest plantations, with different plant covers: birch, chestnut, eucalyptus, walnut, pines, oak and shrublands. These forest soils have in general an acid pH and a high organic matter content, but a small amount of phosphorus. These properties are mainly related to the parent material and the overall climatic conditions of this region, namely the high rainfall scores. The soil under eucalyptus and birch plantations were the driest (13% and 14% on average respectively) vs. the moistest with 27% on average under shrublands. The results regarding microbial activity showed that soils under walnuts have the biggest respiration rates whereas the smallest were under eucalyptus but there were no differences regarding the β-glucosidase enzyme activity. These results show that the forest management, specifically, which tree species are cultivated, has an impact on the soil microbial respiration and should be considered when elaborating forestry exploitation plans, especially in the current scenario of climate change where the C amount that healthy forest soils will be able to fix become crucial.

Keywords: forestry management, forest soils, soil respiration, β-glucosidase, soil C

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INTRODUCTION

Forests all over the world are endangered by different factors such as fragmentation, landscape change, deforestation, pollution or inadequate management (Birdsey and Pan, 2015; Tin et al., 2018; Ruiz-Chután et al., 2025), having detrimental effects on biodiversity (Diaz-Martin and Karubian, 2021) or even on climate change (Delabre et al., 2020). These ecosystems are crucial carbon sinks (Pandey, 2002), both above and below-ground, even though the soil section is still sometimes excluded from the C pools estimations, despite the enormous amount of C stored in it (Robinson, 2007). The soil microbial community plays a key role in the stabilization of organic matter in the forest soil systems, even acting as a C sink in the case of fungi (Cairney, 2012), and harbors numerous ecosystems services (Delgado-Baquerizo et al., 2016).

The soils of Galicia are generally acidic as a result of a humid climate and a strongly subtractive system, which lead to intense leaching, and, frequently, an acidic parent material (Macías et al., 1982; Macías, 1986). Furthermore, vegetation plays an important role in determining the physicochemical and biological soil properties (Chandra et al., 2016; Waymouth et al., 2020; Sui et al., 2022). Therefore, it would be crucial to increase the understanding of the effect due to different tree species on soil properties in order to select the most appropriate plants for a given area.

Globally, forest structure has been subjected to enormous changes in the last decades, with a marked decrease in extension since 1990, whereas the area occupied by forest plantations has increased (Birdsey and Pan, 2015). The species used for the plantations differed depending on the specific pedoclimatic conditions, but in temperate regions natural broadleaved forests have been replaced by trees mainly belonging to the family Pinaceae (Sawada et al., 2021) or Eucalyptus (Tomé et al., 2021). Some authors have noted that natural forest stands have better control of the nutrient cycle and superior soil quality than forest plantations (Chandra et al., 2016; Sui et al., 2022). Soil degradation processes can be related to the conversion from natural to plantation forest (Widyati et al., 2022), involving C and N concentrations decrease (Liao et al., 2012) or modifications in both bacterial and fungal soil communities (Sawada et al., 2021; Wang Q. et al., 2021; Sui et al., 2022).

Several studies have been conducted to understand the interrelationship between tree species, soil microbiota, and the physicochemical properties of forest soils (Mahía et al., 2006; Álvarez et al., 2009; Chandra et al., 2016). The forest soil microbiome can be affected by the different forestry activities such as logging and clear-cutting (Hartmann et al., 2014; Chen et al., 2021), irrigation (Hartmann et al., 2017), fertilization (Addison et al., 2021) or canopy disturbance (van Nuland et al., 2020). Contrasting results have been published for other practices like thinning, with some authors describing a negative impact of this practice on microbial carbon use efficiency (Xue et al., 2023), meanwhile others did not detect and impact on the soil fungal community (Castaño et al., 2018).

The natural primary drivers of the soil microbiome in forest include soil composition and nutrient availability, plant community structure, microbial interactions within the soil, disturbances, succession, and temporal dynamics (Onet et al., 2025). One of the key factors that determines the soil microbial community composition and function of forest soil is the different tree species present in the forest canopy, since a high microhabitat specificity of bacterial communities interacting with forest type has been described (Rodríguez-Rodríguez et al., 2023).

The current study is focused on the analysis of the effect of different forest species on the soil microbial activity and soil properties of forests located in Galicia (on the north-west of Spain) with a temperate-oceanic climate, which favors that the forests in this region are very productive, and this has a clear impact in the tree species that grow on then naturally and the species planted with commercial purposes. We hypothesized that the variability on the different physicochemical and biological soil parameters will be determined by the different tree species, with the bigger differences between the native broadleaf species and the intensive plantations (pines or eucalyptus), in soils developed over the same parent material and under the same climatic conditions.

MATERIALS AND METHODS

Study Area and Soil Sampling

The sampling area is located in Rianxo municipality (Galicia, north-west of Spain, **Figure 1**). The climatic classification applied to this region defines the bioclimate region as typical temperate, oceanic and superior thermo-temperate (Rodríguez-Guitián and Ramil-Rego, 2007). The average temperature in the study area in 2024 was 15.7 °C with an accumulated precipitation of 1774 L m^2, according to a weather station located in the area (42.580074 | −8.804707 WGS84) belonging to Meteogalicia (Xunta de Galicia meteorological network). The parent material in this area is mainly granitic, and the soils are mostly classified as Leptosols and Umbrisols (WRB IUSS Working Group, 2022).

The type of property of these forests is communal, meaning that villagers are the group owners of specific areas of the forest usually near their village, which entails different challenges such as obtaining authorizations to access the property. The sampling was performed in collaboration with the forest owner associations in five different forest communities (Campelo Vilar e Cerqueiras, Araño, Fieitoso, Isorna and Leiro) within Rianxo municipality. Totally, 54 different forest plots were selected with different plantations established, 4 in Campelo Vilar e Cerqueira, 17 in Araño, 2 in Fieitoso, 9 in Isorna and 22 in Leiro (**Figure 1**). The number of replicates sampled differed between the different tree species, depending on what was available in the studied area and the agreement with the forest owners' associations to sample, but the minimum number was three.

Pinus was one of the most representative forest plantations in this area and 30 soil samples under this tree type were collected along the five forest communities (**Figure 1**). The pine stands had different ages: 4 *Pinus pinaster* stands located in Isorna were 40–45 years old; 10 *P. pinaster* and 2 *Pinus radiata* stands, dispersed through the sampling area, were 14–17 years old; and 14 samples, also dispersed, were recent *P. pinaster* plantations (2–4 years old) (**Figure 1**; **Table 1**). The non coniferous species were less represented in this area and the following forest plantations were sampled: 3 soil samples under 4-year old birch plantations (*Betula spp*) and 3 under 4-years old walnut plantations (*Juglans regia*), both located in Leiro; 7 soil samples under 1–17 years old chestnut plantations (*Castanea x hybrida*) located in Leiro, Campelo and Araño; 3 soil samples under 6–14 years old eucalyptus plantations (*Eucalyptus globulus*) located in Leiro and Isorna; 5 soil samples under 2–17 years old oak plantations (mixed of *Quercus rubra* and *Quercus robur*) located in Leiro and Araño; and 3 soil samples under shrublands (*Ulex europaeus*, *Pteridium aquilinum, Erica cinerea, Pterospartum tridentatum, Callunavulgaris, Davoecia cantabrica* and *Cytisus scoparium*) located in Fieitoso, Campelo and Araño (**Figure 1**; **Table 2**). Totally, 30 samples

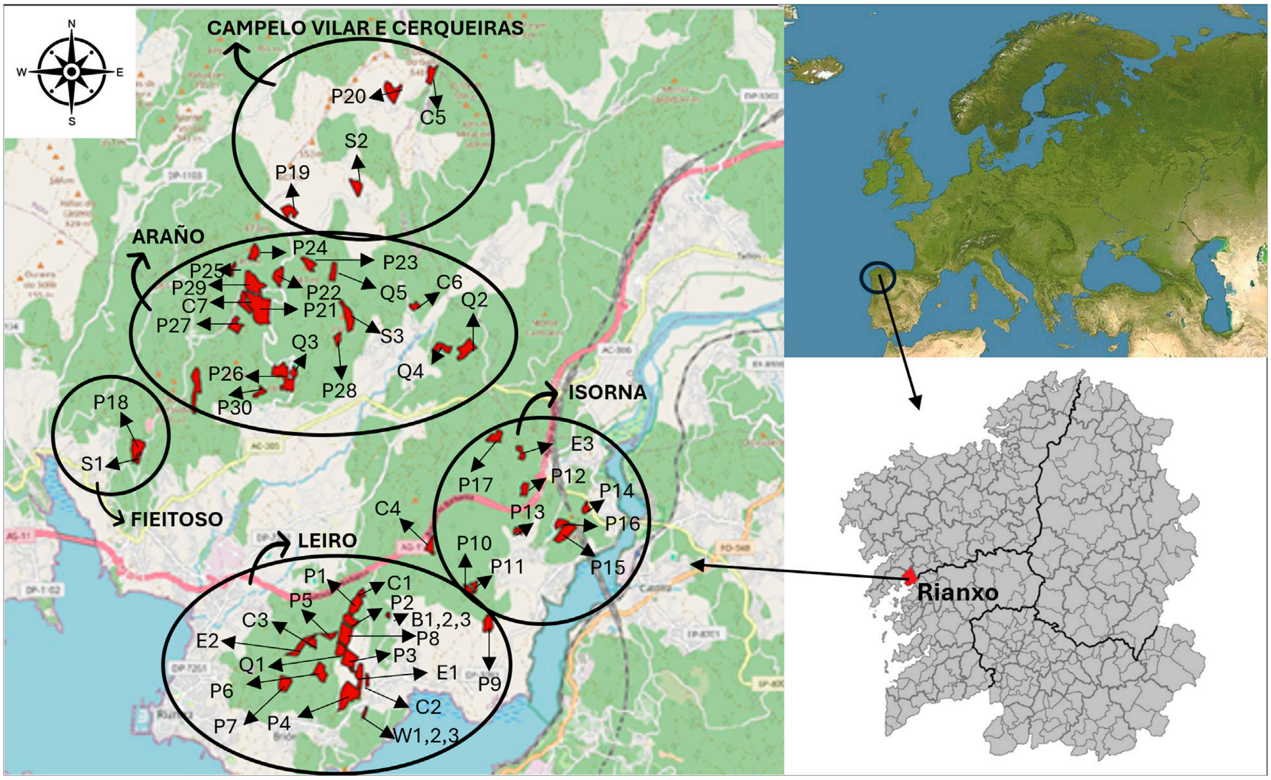

FIGURE 1 | Location of the study area. The sampled plots are marked in red color in the left panel. The uppercase letters indicate the plot vegetation: P (pine), birch (B), walnut (W), chestnut (C), eucalyptus (E), oak (Q) and shrubland (S). The circles marked the different forest communities which are part of the study.

were collected under coniferous forest, 18 under deciduous forest, 3 under eucalyptus and 3 under shrubland at different altitudes (50–485 m above the sea level) (**Tables 1**, **2**).

The soil depth, estimated during the soil sampling, was 50–150 cm, being the deeper soils under the more mature forest stands (**Tables 1**, **2**). This area has a history of wildfires, specifically the communities of Leiro and Isorna which had an important fire event in 2019. The management of the plots in the last 5 years is also shown in **Tables 1**, **2**. In each of the 54 forest stands, 10 subsamples were collected in a zig-zag transect making a composite sample per plot, sampling the 0–20 cm depth soil layer with an auger in the summer of 2024. The samples were immediately transported to the laboratory, sieved (<2 mm) and hand homogenized (quartering method, 5 times). A sub-sample was stored at 4 °C for the microbial analysis, and the rest was dry at 40 °C for the analysis of the soil physicochemical properties.

Soil Physicochemical and Microbial Analyses

Soil physicochemical properties were analyzed using standard procedures (Guitián Ojea and Carballas, 1976; Tan, 1986). Soil texture was determined using the international method of Robison Pipette. Soil water content was determined by the gravimetric method, where soils were oven-dried at 105 °C until constant weight. The pH values were obtained in water (1:2.5), using a pH-meter CRISON, model 2001. Total C and N were determined by elemental analysis using LECO equipment, model TRUSPEC CHNS. Extractable P was measured in soil samples using the Olsen method (Olsen and Sommers, 1982). Soil exchange cations (Ca^{2+}, Mg^{2+}, Na^{+}, K^{+}, Al^{3+}) were extracted using NH_4Cl 1mol L^{-1} (Peech et al., 1947) in 1:10 solution. Ca^{2+}, Mg^{2+} and Al were measured by atomic absorption spectrophotometry; Na^{+} and K^{+} were quantified using emission spectrophotometry. The sum of all these exchange cations was considered the effective cation exchange capacity (eCEC) (Kamprath, 1970).

Regarding microbial analysis, soil microbial activity was estimated by the respiration rate (CO_2 production) by transferring 1 g of soil to a 20 mL glass vial, which was then sealed and incubated for 24 h at room temperature and without light. The CO_2 concentration was determined using a gas chromatograph equipped with FID and using a standard of CO_2. Additionally, the β-glucosidase soil enzyme activity, one enzyme from the C-cycle, was analyzed according to the method of Eivazi and Tabatabai (1988). Briefly, the released p-nitrophenol was determined colorimetrically after incubation of the soil with p-nitrophenyl β-D-glucopyranoside for 2 h at 37 °C.

Data Analysis

The effect of the different forest cover was analyzed by means of standard one-way ANOVA. In cases of significant F statistics, Tukey's significant difference test was used to separate the means.

TABLE 1 | Environmental properties of the pine (P) plots.

Forest community	Trees	Age (years)	Altitude (masl)	Parental rock	Soil depth (cm)	Wildfires (Years)	Management (last 5 years)
Leiro	P1	3	160	Gneis	50	2019	Plantation
	P2	4	180	Gneis	50	2019	-
	P3	3	170	Schists/Gneis	50	2019	Plantation
	P4	14	125	Schists/Gneis	100	-	-
	P5	15	145	Schists/Gneis	50	-	-
	P6	5	110	Schists/Gneis	20	2019	-
	P7	4	90	Granite	50	2019	-
	P8	3	180	Granite	50	2019	Plantation
	P9	14	115	Granite	100	-	-
Isorna	P10	3	175	Granite	50	2019	Plantation/Clearing
	P11	3	140	Granite	50	2019	Plantation/Clearing
	P12	3	105	Granite	100	2019	Plantation/Clearing
	P13	40	50	Granite	150	-	Clearing
	P14	45	65	Granite	150	-	-
	P15	45	70	Granite	150	-	-
	P16	45	80	Granite	150	-	-
	P17	14	165	Granite	100	-	-
Fieitoso	P18	17	155	Schists/Gneis	100	-	Clearing, acacia removing, extensive grazing
Campelo	P19	14	450	Granite	50	-	Clearing, acacia removing
	P20	2	485	Granite	50	-	Plantation
Araño	P21	17	290	Granite	100	-	Clearing, trituration
	P22	2	330	Granite	50	-	Plantation
	P23	3	325	Orthogneis	50	-	Plantation
	P24	3	480	Granite	50	-	Plantation
	P25	3	445	Granite	50	-	Clearing, trituration
	P26	17	160	Granite	150	-	Plantation
	P27	17	315	Granite	100	-	Clearing, trituration
	P28	17	150	Granite	150	-	Clearing, trituration
	P29	17	360	Granite	100	-	Clearing, trituration
	P30	17	145	Granite	150	-	Clearing, trituration

TABLE 2 | Environmental properties of the birch (B), walnut (W), chestnut (C), eucalyptus (E), oak (Q) and shrubland (S) plots.

Forest community	Trees	Age (years)	Altitude (masl)	Parental rock	Soil depth (cm)	Wildfires (Years)	Management (last 5 years)
Leiro	B1	4	85	Granite	50	2019	Plantation
	B2	4	85	Granite	50	2019	Plantation
	B3	4	85	Granite	50	2019	Plantation
Leiro	W1	4	75	Schists/Gneis	50	-	Clearing/Plantation
	W2	4	75	Schists/Gneis	50	-	Clearing/Plantation
	W3	4	75	Schists/Gneis	50	-	Clearing/Plantation
Leiro	C1	4	150	Gneis	50	2019	Plantation
	C2	5	85	Gneis	100	2018	Plantation
	C3	3	110	Schists/Gneis	50	2019	Plantation
	C4	4	125	Granite	50	2019	Plantation
Campelo	C5	14	455	Granite	100	-	-
Araño	C6	1	125	Granite	100	-	Clearing/plantation
	C7	17	295	Granite	100	-	Clearing, trituration
Leiro	E1	6	130	Granite	50	2019	-
	E2	15	120	Schists/Gneis	50	2019	-
Isorna	E3	14	90	Granite	50	2019	-
Leiro	Q1	17	160	Schists/Gneis	50	2007/2010/2016	Plantation
Araño	Q2	2	190	Granite	50	-	Eucalyptus removal
	Q3	17	135	Granite	150	-	Clearing, trituration
	Q4	2	140	Granite	100	-	Eucalyptus removal
	Q5	17	195	Orthogneis	100	-	Clearing
Fieitoso	S1	-	150	Schists/Gneis	50	-	Intensive grazing
Campelo	S2	-	375	Granite	50	-	Clearing
Araño	S3	-	200	Granite	100	-	Eucalyptus removal (2023)

TABLE 3 | Soil physicochemical properties under different types of forest cover. Average ± SE.

Forest cover	pH	SOM (%)	N (%)	C/N	P (mg kg^{-1})	Na$^+$ (cmol kg^{-1})	K$^+$ (cmol kg^{-1})	Al^{3+} (cmol kg^{-1})	Sat Al^{3+} (%)
Birch	4.92 ± 0.02	12.9 ± 0.4	0.45 ± 0.02	16.5 ± 0.2	6.0 ± 0.1	0.15 ± 0.03	0.29 ± 0.07	5.83 ± 0.62	63 ± 11
Chesnut	4.93 ± 0.16	15.5 ± 1.9	0.54 ± 0.06	17.0 ± 1.1	7.8 ± 1.5	0.19 ± 0.05	0.18 ± 0.02	6.31 ± 0.58	83 ± 2
Eucalyptus	4.98 ± 0.04	12.1 ± 2.3	0.41 ± 0.09	17.4 ± 1.8	4.0 ± 0.3	0.14 ± 0.03	0.25 ± 0.13	4.70 ± 1.49	72 ± 20
Walnut	5.06 ± 0.05	20.9 ± 0.4	0.69 ± 0.01	17.6 ± 0.1	7.6 ± 0.6	0.14 ± 0.02	0.22 ± 0.05	5.93 ± 0.25	75 ± 10
Oak	4.72 ± 0.10	15.4 ± 0.8	0.61 ± 0.03	14.8 ± 0.8	8.4 ± 1.5	0.15 ± 0.04	0.24 ± 0.05	7.43 ± 0.59	79 ± 7
Shrubland	4.63 ± 0.17	14.2 ± 0.8	0.54 ± 0.04	15.4 ± 1.6	7.2 ± 0.9	0.09 ± 0.01	0.11 ± 0.02	4.88 ± 0.91	90 ± 1
Pine	4.75 ± 0.05	15.1 ± 0.8	0.54 ± 0.03	16.3 ± 0.4	7.0 ± 0.8	0.14 ± 0.02	0.17 ± 0.01	6.58 ± 0.28	86 ± 1

There are no significant differences between groups ($p > 0.05$), Krustal-Wallis test was used for pH and K and ANOVA test for the rest ($n = 54$).

For the properties with non-normal distribution Kruskal-Wallis test was used. The correlation between the different soil physicochemical properties and the microbial activity parameters was analyzed using Pearson correlation coefficients at the $p < 0.05$ level. The values corresponding to all the physicochemical and biological soil properties were subjected to a redundancy analysis (RDA) to elucidate the main differences between the different forest covers and explore the relationship with the environmental variables. The statistical analyses were performed using the R software package (R studio, version 4.1.0).

RESULTS AND DISCUSSION

Soil Physicochemical Properties

The dominant soil texture in this area was sandy, with 76% of soils having a sandy loam texture, 22% had a loamy sand texture and 2% were sandy soils, in accordance with the granite material from which they originate (Macías et al., 1982). These forest soils have, on average, an acid pH (between 4.63 and 5.6), a high content of soil organic matter (SOM) (between 12.1% and 20.9%), with N concentrations ranging 0.41%–0.69% and C/N ratio between 14.8 and 17.6, but containing small phosphorus concentrations (between 4.0 and 8.4 mg P kg^{-1}) (**Table 3**). The statistical analysis showed no significant differences for the physiochemical properties of these soils between the different forest species, but it was observed that the soils under oak, pine and shrublands had the most acidic pH, meanwhile soils under birch and eucalyptus showed the lower amounts of C, SOM and P (**Table 3**). The low available P content in all these forest soils can be related to the acid pH, since at these values P is retained by the variable charge soil components which are positively charged, as happens for most of the forest soils in Galicia (García-Rodeja and Gil-Sotres, 1997; Eimil-Fraga et al., 2014).

These properties are mainly related to the climatic conditions of this region, namely the elevated precipitation since the humid climate favors the process of leaching and acidification, and are also due to the acidic nature of the parent material (Macías et al., 1982; Macías, 1986; García-Rodeja et al., 2023). There are numerous studies on the influence of different tree species on soil properties, but the results are inconsistent. Some authors point out that conifers acidify the soil and are therefore associated with degradation and podzolization processes, especially in cold regions (Matzner and Ulrich, 1983; Augusto et al., 1998; van Breemen et al., 2000, among others). More recent articles also describe a better quality of deciduous forest soils compared to coniferous forests and relate this to the quality of the leaf litter (Sui et al., 2022).

Conversely, in other areas, some authors indicate that vegetation may be a secondary factor influencing soil properties, subordinate to climate and parent material (Macías et al., 1982). Priha and Smolander (1999) state that it takes a long time for trees to cause changes in the soil, which could explain the lack of differences in the previously mentioned soil properties, since more than half of the forest stands analyzed in the present study were recent plantations (<6 years) (**Tables 1**, **2**). To note

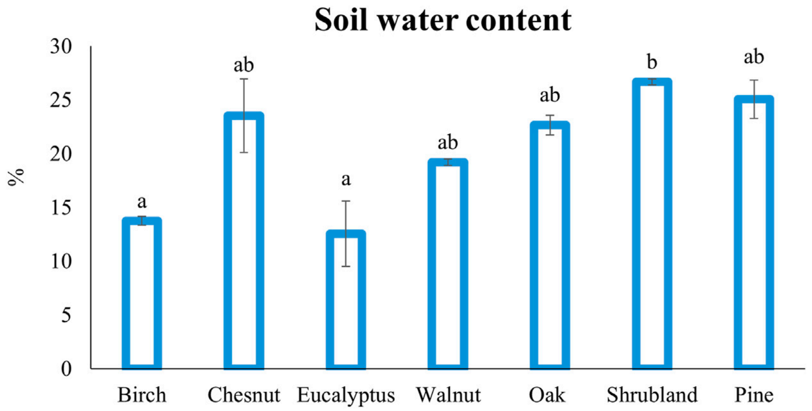

FIGURE 2 | Soil water content (%) under the different type of forest cover. Different letters indicate significant differences, Kruskal-Wallis test ($p < 0.05$) (n = 54).

that the soil solution is more sensitive than the solid phase for the detection of possible changes caused by anthropogenic activities (Álvarez et al., 2002; Álvarez et al., 2005). In this sense, these authors observed a significant effect of tree species on the pH of the liquid phase of Galician soils and on the most labile forms of aluminum (labile monomeric aluminum, and Al-F and Al-OH complexes), which were higher in soils under pine.

Soil moisture showed significant differences between some of the different forest plantations (**Figure 2**). Low soil water content was detected under eucalyptus and birch (13% and 14% on average, respectively) in contrast with higher values detected in the soils under shrubland (27%) ($p = 0.042$ and $p = 0.035$, respectively). The rest of the samples presented intermediate values, namely 19% for walnuts, 23% for oaks, 24% for chestnuts and 25% for pine (**Figure 2**). The ability of eucalyptus trees to extract a high amount of soil water has been described in the literature (Robinson et al., 2006), but other authors stated that eucalyptus water depletion is a myth and is more related to an inappropriate management of the plantation than to the trees themselves (Medeiros et al., 2025). The capacity of birch to decrease the water content of the topsoil has been well described, compared to coniferous trees (spruce) (Špulák et al., 2021), but in the mentioned study the stands were older than the ones in the current research.

Both birch and eucalyptus stands were established over shallow soils (~50 cm) that suffered the impact of a wildfire in 2019, whereas for the other species there were wildfire events in just some of the field replicates (pines, oaks and chestnuts) or a complete lack of these events in the case of walnut and shrubs (**Table 2**). If the disturbance of vegetation by fire is substantial enough, the resulting perturbations to soils can persist for years, resulting in lower water contents (Cooperdock et al., 2020). The soils under these trees showed the lower SOM content, 12.1% under eucalyptus and 12.9% under birch (**Table 3**) compared with the other species. The low water content of these samples might be related to the fire event, the soil management for the tree's establishment or the low SOM content which would increase water retention under the other species (Rawls et al., 2003). Indeed, we found a significant positive correlation between soil water content and soil organic matter (r = 0.29, $p < 0.05$) (**Figure 3**).

The bigger soil moisture in the soils under shrubland might be related to the afforestation process in terms of tree water consumption (Herron et al., 2022; Farley et al., 2004), being the differences in tree physiology, plantation design and management and the forestry operations the factors that affect the most to forest hydrology (van Dijk and Keenan, 2007). The permanent soil cover in the shrubland and the shrub roots (Gao et al., 2021) favor the high-water content in those soils. The lack of previous fire events in these plots (**Table 2**) might be another positive factor for the biggest soil water content.

On the other hand, the soils under shrubs showed the lowest effective cation exchange capacity, meanwhile soils under birch, oak and walnut had the highest values (**Figure 4A**). Conversely, other authors detected bigger eCEC scores under pine compared with oak trees in acid forest soils (Gruba and Mulder, 2015). The highest eCEC values coincide with the higher levelsof organic matter and/or higher pH (**Table 3**), which favors the increase of the negative charges in variable charge components (Gruba and Mulder, 2015). There were no differences regarding the concentration of Mg^{2+}, Ca^{2+}, Na^{+}, K^{+} and Al^{3+} (**Table 3**; **Figures 4B,C**) among the different plantations.

The amount of Al^{3+} (on average between 4.7 and 7.43 cmol kg^{-1}) was quite high, which is common in these forest granitic soils (Macías et al., 1982). These Al^{3+} concentrations represented on average between 63% and 90% saturation of the exchange complex (**Table 3**), with practically all samples having values > 60% Al^{3+} saturation, indicative of alic soils, that can limit plant growth (Kochian et al., 2004; Gupta et al., 2013). The percentage of Al^{3+} saturation was higher under shrublands (90%), pines (86%) and chestnut (83%), even though this difference was not significant. In addition, an elevated Al^{3+} saturation under pine has been previously described (Álvarez et al., 2002).

However, despite the high Al^{3+} saturation of these forest soils, timber production in Galicia is high in the context of the temperate-humid region (Corbelle-Rico and Tubío-Sánchez,

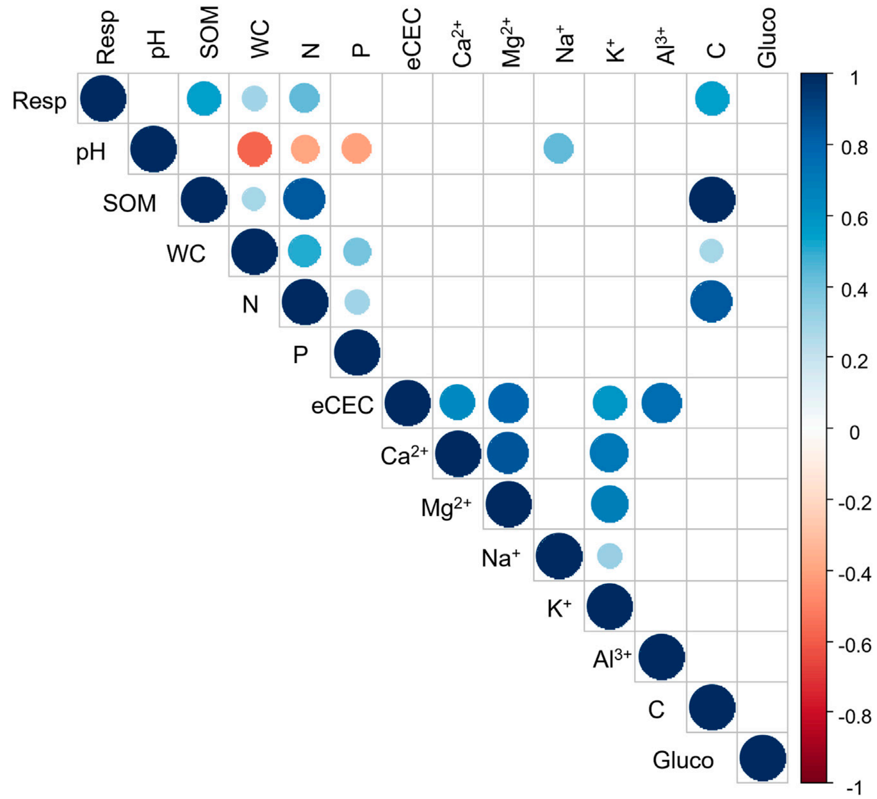

FIGURE 3 | Pearson correlation of the different soil physicochemical properties. Blue dots mean significant positive correlations and red dots mean significant negative correlations, the size of the dot is proportional of the correlation coefficient ($p < 0.05$) ($n = 54$). Resp: respiration; SOM: soil organic matter; WC: water content; eCEC: effective cation exchange capacity; Gluco: β-glucosidase activity.

2018). This may be related to different causes (species adaptation to these soils, mycorrhization, etc.), but with respect to Al^{3+}, it has been shown that organic matter plays an important role in reducing the toxicity of this element, complexing Al^{3+} in the form of polymers or monomers (Álvarez et al., 2002; Álvarez et al., 2005; Eimil-Fraga et al., 2015; Eimil-Fraga et al., 2016). In addition, anions such as sulfate or fluoride can also bind to Al (Al-SO_4, Al-F), decreasing its toxicity (Álvarez et al., 2005; Eimil-Fraga et al., 2016).

It was also observed that soils under chestnut, shrubland and pines had the lowest concentration of Mg^{2+} and Ca^{2+} (**Figures 4B,C**), even though these differences were not significant. To cope with the Al toxicity some species demand large quantities of Ca^{2+} and Mg^{2+} to reach high levels of productivity (Rocha et al., 2019). In fact, the Ca/Al ratio in soils, leaves and roots has been used as an index to evaluate the toxicity of this element (Cronan and Grigal, 1995; Álvarez et al., 2005; Eimil-Fraga et al., 2016). Kinraide (2003) and Kinraide et al. (2004) referred that the addition of Mg^{2+} to the external medium relieved Al toxicity in many plants. We detected a correlation between the exchangeable Ca^{2+} and Mg^{2+} in our samples with $r = 0.85$, $p < 0.05$ (**Figure 3**). The same trend was described in base-poor soils by other authors (Rocha et al., 2019). The lower concentrations of Ca^{2+} and Mg^{2+} in the soil under chestnuts, shrubland and pines could be a result of the major requirements of these plants to tolerate these high Al concentrations (**Table 3**).

Soil Microbial Activity

The results regarding microbial activity showed that soil under broadleaf species (birch, chestnut, walnut and oaks) have bigger respiration rates than soil under pines, shrublands and especially under eucalyptus (**Figure 5B**). The only significant differences, when divided at the species level, were between the soil respiration under eucalyptus and walnuts, with average values of 537 ± 211 ppm CO_2 g^{-1} and 1440 ± 97 ppm CO_2 g^{-1}, respectively, with the soil respiration under the rest of the tree species being between those values (**Figure 5A**).

The soil under walnuts showed the biggest amount of SOM (20.9%) meanwhile the soils under eucalyptus had the lowest values (12.1%) (**Table 3**). Even though these average values were not significantly different, soil respiration was positively correlated with soil organic matter ($r = 0.54$), total nitrogen ($r = 0.43$) and total C ($r = 0.54$) (**Figure 3**). On the other hand, walnut leaf litter has a big amount of phenolic compounds (Mungai and Motavalli, 2006) which can inhibit Gram-positive bacteria but do not affect fungi (Pereira et al., 2007), which are the main responsible of respiration on forest soils (Fransson, 2012).

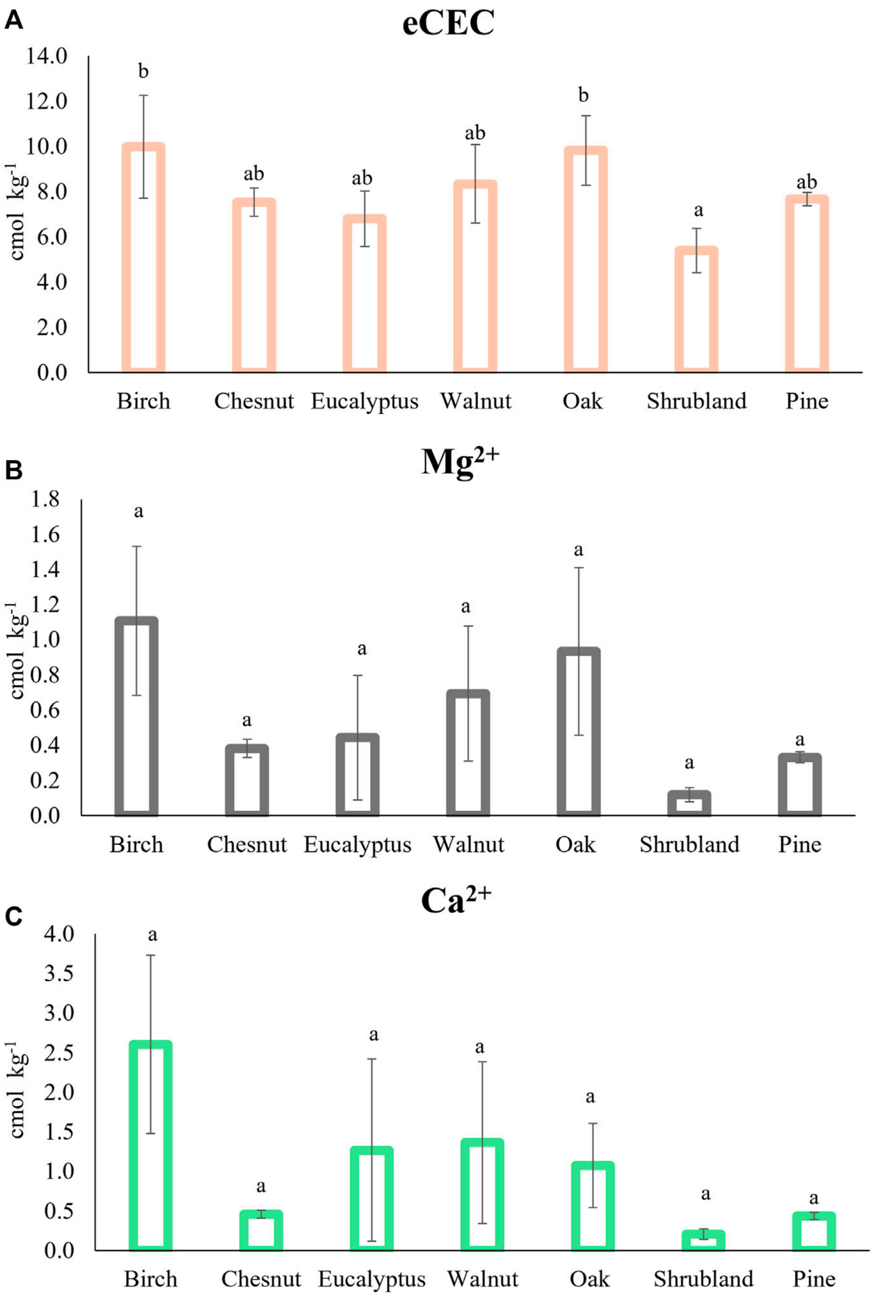

FIGURE 4 | Effective cation exchange capacity (eCEC) **(A)**, exchangeable Mg^{2+} **(B)** and Ca^{2+} **(C)** under the different the different type of forest cover. Different letters indicate significant differences ($p < 0.05$) Krustal-Wallis test was used for Mg^{2+} and Ca^{2+} and ANOVA test for eCEC (n = 54).

The walnut plots did not suffer wildfires recently, whereas all the eucalyptus plots were burnt in 2019, therefore the smaller values in respiration for the latter could be a consequence of the wildfire event 5 years ago. However, recent metanalysis studies reveal that generally after 5 years total soil respiration recovers to pre-fire values (Zhou et al., 2023) and specifically for temperate forests the recovery time will be around 3 years (Gui et al., 2023). In general, microbial activity changes can be transitory, and their values can reach pre-fire ones, but diversity changes seem to be maintained at a longer time (Barreiro and Raviña, 2021).

When the values of soil respiration under de deciduous trees were pooled together (**Figure 5B**), it was observed that the respiration under eucalyptus was significantly lower than under the deciduous forests, but the coniferous values were between them. These results are in agreement with other authors (Raich and Potter, 1995; Hibbard et al., 2005) that did not find statistical differences in soil respiration between

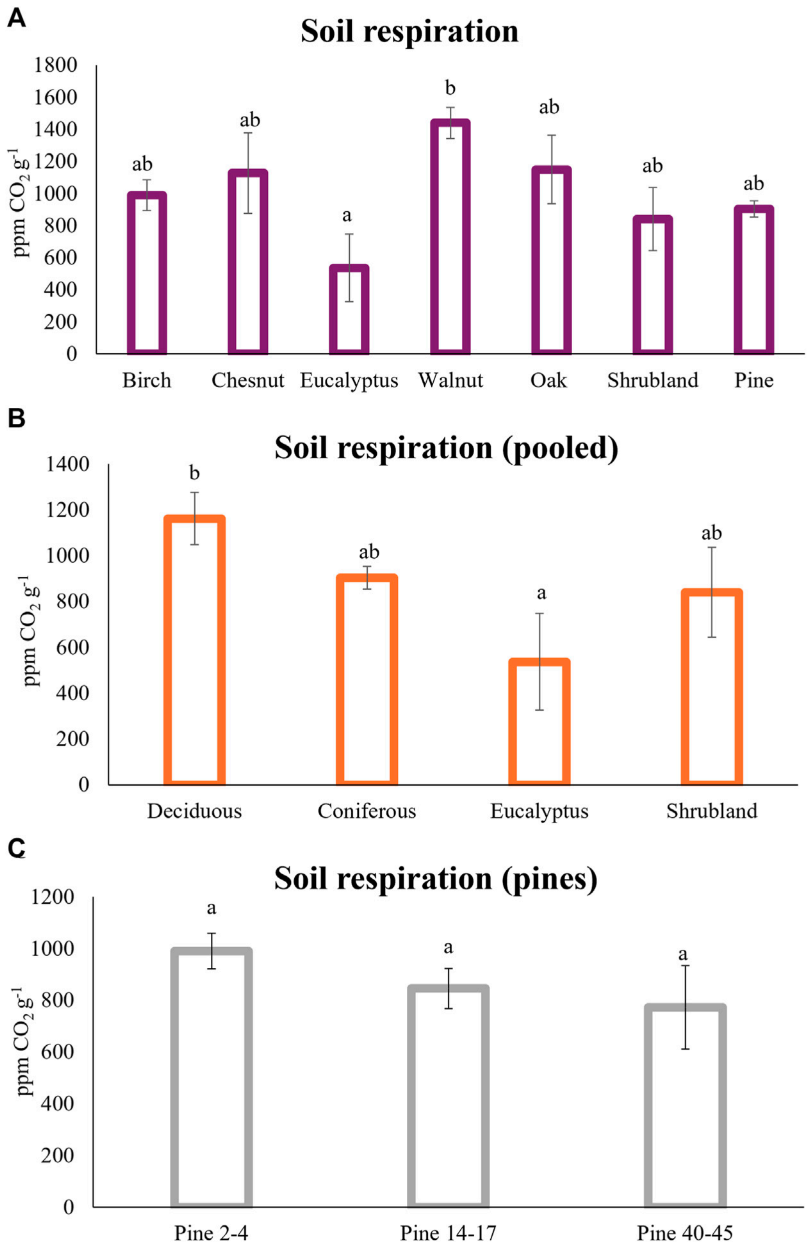

FIGURE 5 | Soil respiration (ppm CO_2 g^{-1}) under the different tree plantations **(A)**; with the deciduous species pool together (oak, birch, walnut and chestnut) **(B)**; and under pine plantations with different ages **(C)**. Different letters indicate significant differences, ANOVA test ($p < 0.05$).

coniferous and deciduous forests. The litter input provided by the deciduous trees had a strong positive impact on soil respiration (Zhang et al., 2020). Similarly, soil respiration could increase under deciduous tree species, compared with evergreen tree species, due the bigger root exudation rates and annual root exudate carbon fluxes of the deciduous trees (Wang Y. et al., 2021).

The forest plantations with lower soil water content were birch and eucalyptus, and correlations between soil respiration and soil water content were detected ($r = 029$, $p < 0.05$) (**Figure 3**). However the soil respiration was lower under the eucalyptus plantation, meanwhile the values under birch were in the same order as the rest of the broadleaf species (**Figure 5A**). The dependency on the soil water content of soil respiration under eucalyptus has been described (Epron et al., 2004), and these authors also found a correlation of the soil respiration with both leaf and total aboveground litter in eucalyptus plantations but this was not analyzed in the current study. Other authors have described a modification in the microbial community structure within eucalyptus plantations, specifically a decrease

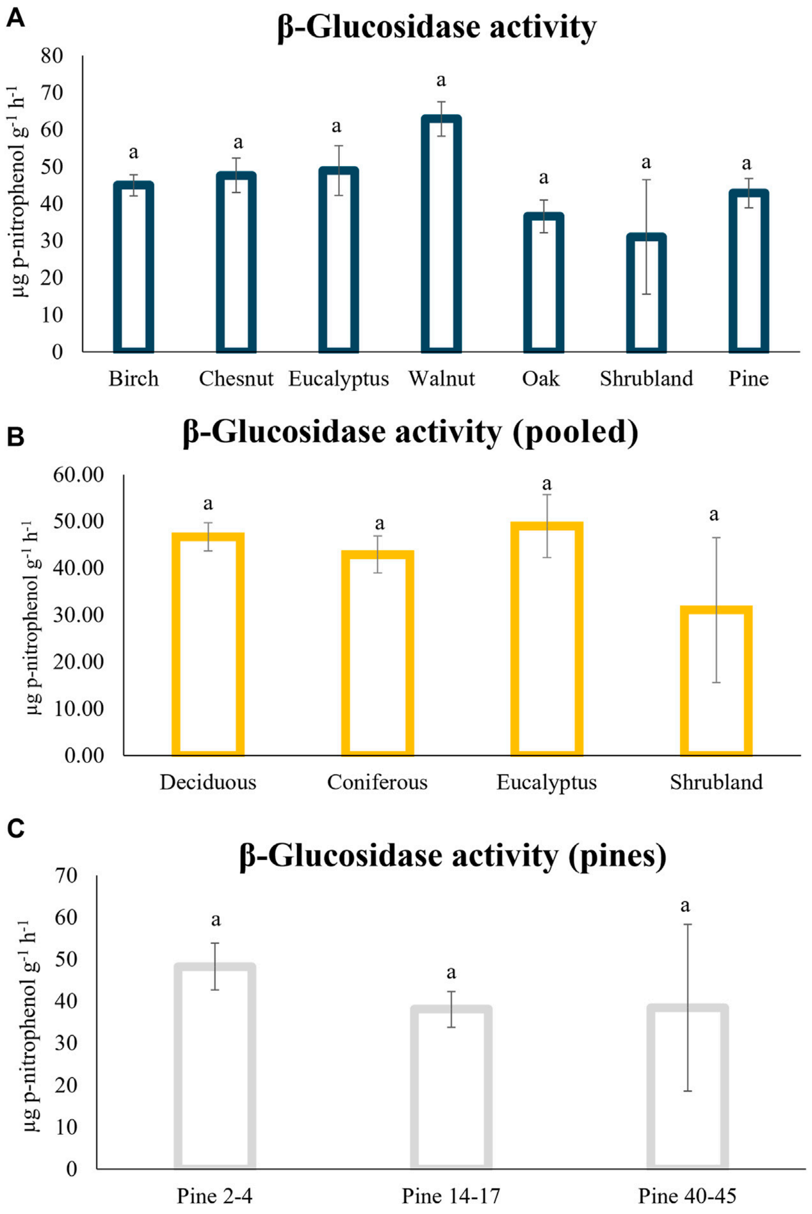

FIGURE 6 | β-Glucosidase soil enzyme activity under the different tree plantations **(A)** with the deciduous species pool together (oak, birch, walnut and chestnut) **(B)**; and under pine plantations with different ages **(C)**. Different letters indicate significant differences, ANOVA test (p < 0.05).

in the fungal dominance (Behera and Sahani, 2003), which could explain the lower soil respiration rates under this forest plantation (**Figure 5A**).

For the pine plantations, soil respiration was also compared between stands of different ages, but no differences were observed (**Figure 5C**), even though the average values tended to decrease with the tree longevity, from 991 ± 69 ppm CO_2 g^{-1} for the 2–4 years pine stand to 774 ± 162 ppm CO_2 g^{-1} for the older pine stands (40–45 years). A similar decrease with age stands under pine was detected by Zhao et al. (2016).

In the analysis of the β-glucosidase enzyme activity no differences were detected for the soils under the different forest plantations, with average values between 60 ± 5 µg p-nitrophenol g^{-1} h^{-1} for soils under walnuts and 31 ± 15 µg p-nitrophenol g^{-1} h^{-1} for soils under shrublands. No differences were found neither when the values for the deciduous trees were pooled together for the distinct age stands in the case on the pine plantations (**Figures 6A–C**). Other studies described bigger β-glucosidase values under pines compared with oak (Błońska and Lasota, 2017).

Within our pine plantations, the young stands (2–4 years old) showed slightly higher average activity (48 ± 6 µg p-nitrophenol g^{-1} h^{-1}) than the older stands (38 ± 4 and 38 ± 20 µg p-nitrophenol g^{-1} h^{-1} for 14–17 and 40–45 years old stands respectively), even though this difference was not significant (**Figure 6C**). Wang et al. (2019), using plantations within the

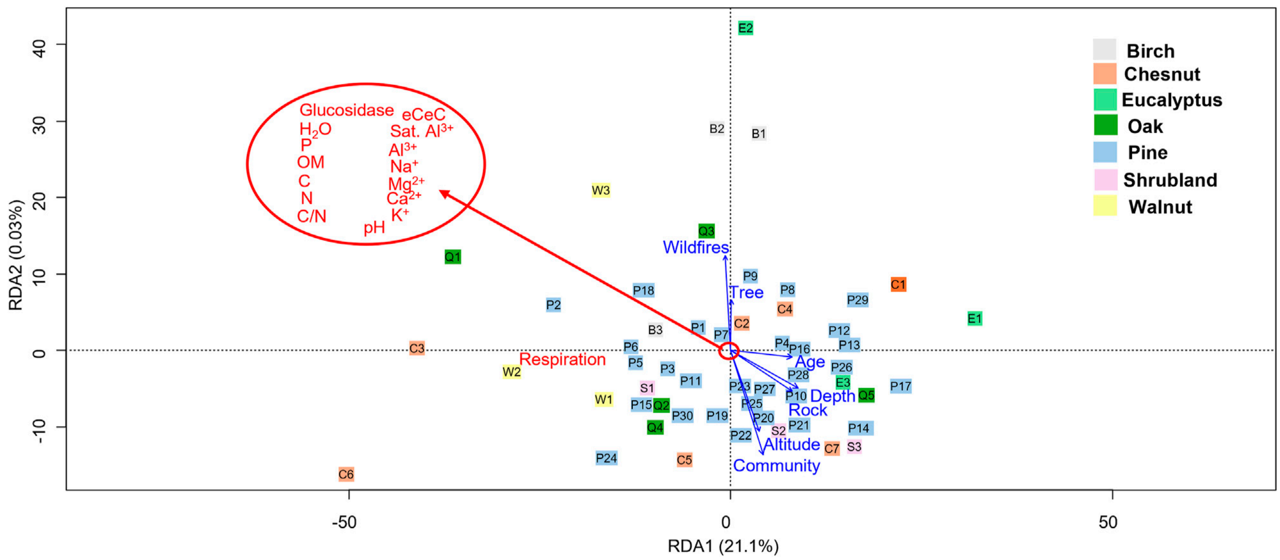

FIGURE 7 | Redundancy analysis (RDA) of physicochemical and biological soil properties of the 54 soils under different forest covers. The uppercase letters indicate the plot vegetation: P (pine), birch (B), walnut (W), chestnut (C), eucalyptus (E), oak (Q) and shrubland (S).

same age range also found bigger β-glucosidase activity in the younger stands (3–6 years old) compared with stands that were 12–18 years old. However, these authors detected an increase in this enzyme activity in the soils under the oldest tree stands that was not found in our samples.

The role of this enzyme is key in the cellulose degradation (Zang et al., 2018), since β-glucosidases complete the final step of cellulose hydrolysis by converting cellobiose to glucose. This enzymatic activity is key in the C-cycling and can be used as a soil quality indicator (Stott et al., 2010). This decomposition process is stand-specific with a particularly negative effect in the case of evergreen tree litter (Joly et al., 2017) that was not detected in our study.

Soil enzyme activity in general, including β-glucosidase activity, usually correlated with soil pH, soil organic carbon and total nitrogen and edaphic properties, had higher importance in explaining enzyme variability than climate or stand properties (Oliveira et al., 2025). The limited variability observed in most of the edaphic properties within our samples (**Table 3**) might explain the lack of differences between the various forest stands (**Figure 6A**) or the non-significant correlation with such properties (**Figure 3**).

The values of this activity were lower than others described under oak and eucalyptus in the same region and with similar physicochemical properties (Lombao et al., 2015), but the referred soil had double the amount of moisture compared to the soil of the present study. In this case, the sampling was performed in summer, where a marked decrease in precipitation occurs every year, leading to a decrease in the water content, which might be the responsible for the lower enzyme activity detected in our samples. This suggest that β-glucosidase was sensitive to changing soil moisture regimes, as reported by other authors (Zhang et al., 2011). However, other studies in coniferous forest soils detected an impact of seasonality in the β-glucosidase gene pool, but not in the activity itself (Pathan et al., 2017). Different studies that identify differences between the soil β-glucosidase activity under different forest stands (Salazar et al., 2011) usually refers to adult trees, meanwhile in our study most of the trees are <17 years old.

Figure 7 represents the redundancy analysis (RDA) of the whole data set. Despite of the differences described for water content, eCEC and soil respiration between different forest plantations, when all the physiochemical and biological properties were analyzed together in the RDA analysis no structural differences were detected. The permutation test for the RDA reduced model showed that the age of the stand was the only significant factor ($p < 0.05$) affecting the soil properties, meanwhile wildfire events were marginally significant ($p = 0.056$). For the other environmental factors considered, community where the forest belongs, altitude, tree species, parental rock, and soil depth had no significant effect on the analyzed soil properties ($p > 0.05$). The soil depth and parental rock were correlated as the deeper soils developed generally over granitic rocks; as well as the altitude and the community, since some communities were located at higher altitudes than others (**Figure 7**; **Tables 1**, **2**).

The first component, which explained 21.1% of the variability, was related to the soil respiration, bigger in the soil samples with the high amount of SOM (**Figure 7**), in agreement with what has been previously published about the relation of CO_2 efflux and carbon pools in roots and soils (Zhou et al., 2013). The rest of the soil properties did not have a clear impact on the distribution of the different samples in the RDA analysis. The influence of the stand age might be hindering the effect of the forest type, which has legacy effects in defining soil community composition (Rodríguez-Rodríguez et al., 2023). Forest age and structure have a noticeable effect on the soil nutrients and metals that tend to accumulate in soil rather than the litter (Lucas-Borja et al., 2019).

Regarding the soil microbial activity, younger stands have lower soil enzymatic activities and respiration, related with soil moisture, litterfall, soil organic matter and water holding capacity, compared with older stands (Lucas-Borja et al., 2016). However clear correlations between the age of the stand and the soil respiration and β-glucosidase activity were not detected in our study, probably due to the young age of most of the stands analyzed. Our hypothesis regarding the influence of the tree species in the soil properties was not fulfilled, most likely due to the different age of the stands which acted as a confounding factor.

CONCLUSION

The results of the current research indicate that tree species do not significantly affect soil pH, SOM, C, N, P or exchangeable cations, likely due to the analyses being restricted to the solid soil phase and the different ages of the plantations.

In contrast, three species influenced soil moisture and microbial respiration, with soils under eucalyptus exhibiting the lowest values for both parameters. These findings are critical for informing forestry management plans, particularly under current climate change scenarios, where productive forests serve as significant C sinks, yet management practices can markedly alter soil C pools.

Considering the entire spectrum of soil properties, stand age and historical wildfire events emerged as primary drivers of the observed soil variability. Further research is needed to elucidate species impact on soil properties and to guide forest management under specific edapho-climatic conditions. Integrating microbial community analysis with functional assessments, alongside evaluating long-term wildfire and management impacts is essential in the context of climate change.

DATA AVAILABILITY STATEMENT

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

AUTHOR CONTRIBUTIONS

AB and AM-G participated on software, data curation, writing-Original draft preparation, visualization, and investigation. RC-D participated in software, data curation, visualization and investigation. MD-R, AN-D, and MF-S participated in conceptualization, methodology, writing-Original draft preparation, visualization, supervision, and validation. EÁ-R participated in visualization, supervision, validation, writing-reviewing and editing. All authors contributed to the article and approved the submitted version.

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CONFLICT OF INTEREST

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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REFERENCES

Addison, S. L., Smaill, S. J., Garrett, L. G., and Wakelin, S. A. (2021). Fertiliser Use Has Multi-Decadal Effects on Microbial Diversity and Functionality of Forest Soils. *Appl. Soil Ecol.* 163, 103964. doi:10.1016/j.apsoil.2021.103964

Álvarez, E., Monterroso, C., and Marcos, M. F. (2002). Aluminium Fractionation in Galician (NW Spain) Forest Soils as Related to Vegetation and Parent Material. *For. Ecol. Manag.* 166, 193–206. doi:10.1016/S0378-1127(01)00658-2

Álvarez, E., Fernández-Marcos, M. L., Monterroso, C., and Fernández-Sanjurjo, M. J. (2005). Application of Aluminium Toxicity Indices to Soils Under Various Forest Species. *For. Ecol. Manag.* 211, 227–239. doi:10.1016/j.foreco.2005.02.044

Álvarez, E., Torrado, V. T., Fernández-Marcos, M. L., and Díaz-Raviña, M. (2009). Microbial Biomass and Activity in a Forest Soil Under Different Tree Species. *Electron. J. Food, Agric. Chem.* 8, 878–887.

Augusto, L., Bonnaud, P., and Ranger, J. (1998). Impact of Tree Species on Forest Soil Acidification. *For. Ecol. Manag.* 105, 67–78. doi:10.1016/S0378-1127(97)00270-3

Barreiro, A., and Raviña, D. (2021). Fire Impacts on Soil Microorganisms: Mass, Activity, and Diversity. *Curr. Opin. Environ. Sci. and Health* 22, 100264. doi:10.1016/j.coesh.2021.100264

Behera, N., and Sahani, U. (2003). Soil Microbial Biomass and Activity in Response to Eucalyptus Plantation and Natural Regeneration on Tropical Soil. *For. Ecol. Manag.* 174, 1–11. doi:10.1016/S0378-1127(02)00057-9

Birdsey, R., and Pan, Y. (2015). Trends in Management of the World's Forests and Impacts on Carbon Stocks. *For. Ecol. Manag.* 355, 83–90. doi:10.1016/j.foreco.2015.04.031

Błońska, E., and Lasota, J. (2017). "β-Glucosidase Activity of Forest Soil as an Indicator of Soil Carbon Accumulation," in *Soil Biological Communities and Ecosystem Resilience* (Springer International Publishing), 253–263.

Cairney, J. W. G. (2012). Extramatrical Mycelia of Ectomycorrhizal Fungi as Moderators of Carbon Dynamics in Forest Soil. *Soil Biol. Biochem.* 47, 198–208. doi:10.1016/j.soilbio.2011.12.029

Castaño, C., Alday, J. G., Lindahl, B. D., Martínez de Aragón, J., de-Miguel, S., Colinas, C., et al. (2018). Lack of Thinning Effects Over Inter-Annual Changes in Soil Fungal Community and Diversity in a Mediterranean Pine Forest. *For. Ecol. Manag.* 424, 420–427. doi:10.1016/j.foreco.2018.05.004

Chandra, L. R., Gupta, S., Pande, V., and Singh, N. (2016). Impact of Forest Vegetation on Soil Characteristics: A Correlation Between Soil Biological and Physico-Chemical Properties. *3 Biotech.* 6, 188–12. doi:10.1007/s13205-016-0510-y

Chen, J., Chazdon, R. L., Swenson, N. G., Xu, H., and Luo, T. (2021). Drivers of Soil Microbial Community Assembly During Recovery from Selective Logging and Clear-Cutting. *J. Appl. Ecol.* 58, 2231–2242. doi:10.1111/1365-2664.13976

Cooperdock, S. C., Hawkes, C. V., Xu, D. R., and Breecker, D. O. (2020). Soil Water Content and Soil Respiration Rates Are Reduced for Years Following Wildfire in a Hot and Dry Climate. *Glob. Biogeochem. Cycles* 34, e2020GB006699. doi:10.1029/2020GB006699

Corbelle-Rico, E. J., and Tubío-Sánchez, M. J. (2018). Productivism and Abandonment: The Two Sides of Forest Transition in Galicia (Spain), 1966-2009. *Rev. Bosque* 39, 457–467. doi:10.4067/S0717-92002018000300457

Cronan, C. S., and Grigal, D. F. (1995). Use of calcium/aluminum Ratios as Indicators of Stress in Forest Ecosystems. *J. Environ. Qual.* 24, 209–226. doi:10.2134/jeq1995.00472425002400020002x

Delabre, I., Boyd, E., Brockhaus, M., Carton, W., Krause, T., Newell, P., et al. (2020). Unearthing the Myths of Global Sustainable Forest Governance. *Glob. Sustain.* 3, e16. doi:10.1017/sus.2020.11

Delgado-Baquerizo, M., Maestre, F. T., Reich, P. B., Jeffries, T. C., Gaitan, J. J., Encinar, D., et al. (2016). Microbial Diversity Drives Multifunctionality in Terrestrial Ecosystems. *Nat. Commun.* 7, 10541. doi:10.1038/ncomms10541

Diaz-Martin, Z., and Karubian, J. (2021). Forest Cover at Landscape Scales Increases Male and Female Gametic Diversity of Palm Seedlings. *Mol. Ecol.* 30, 4353–4367. doi:10.1111/mec.16060

Eimil-Fraga, C., Rodríguez-Soalleiro, R., Sánchez-Rodríguez, F., Pérez-Cruzado, C., and Álvarez-Rodríguez, E. (2014). Significance of Bedrock as a Site Factor Determining Nutritional Status and Growth of Maritime Pine. *For. Ecol. Manag.* 331, 19–24. doi:10.1016/j.foreco.2014.07.024

Eimil-Fraga, C., Álvarez-Rodríguez, E., Rodríguez-Soalleiro, R., and Fernández-Sanjurjo, M. J. (2015). Influence of Parent Material on the Aluminium Fractions in Acidic Soils Under *Pinus pinaster* in Galicia (NW Spain). *Geoderma* 255, 50–57. doi:10.1016/j.geoderma.2015.04.026

Eimil-Fraga, C., Fernández-Sanjurjo, M. J., Rodríguez-Soalleiro, R., and Álvarez-Rodríguez, E. (2016). Aluminium Toxicity Risk for *Pinus pinaster* in Acid Soils (Galicia, NW Spain). *Land Degrad. and Dev.* 27, 1731–1739. doi:10.1002/ldr.2539

Eivazi, F., and Tabatabai, M. A. (1988). Glucosidases and Galactosidases in Soils. *Soil Biol. Biochem.* 20, 601–606. doi:10.1016/0038-0717(88)90141-1

Epron, D., Nouvellon, Y., Roupsard, O., Mouvondy, W., Mabiala, A., Saint-André, L., et al. (2004). Spatial and Temporal Variations of Soil Respiration in a Eucalyptus Plantation in Congo. *For. Ecol. Manag.* 202, 149–160. doi:10.1016/j.foreco.2004.07.019

Farley, K. A., Kelly, E. F., and Hofstede, R. G. M. (2004). Soil Organic Carbon and Water Retention After Conversion of Grasslands to Pine Plantations in the Ecuadorian Andes. *Ecosystems* 7, 729–739. doi:10.1007/s10021-004-0047-5

Fransson, P. (2012). Elevated CO_2 Impacts Ectomycorrhiza-Mediated Forest Soil Carbon Flow: Fungal Biomass Production, Respiration and Exudation. *Fungal Ecol.* 5, 85–98. doi:10.1016/j.funeco.2011.10.001

Gao, Z., Hu, X., and Li, X. Y. (2021). Changes in Soil Water Retention and Content During Shrub Encroachment Process in Inner Mongolia, Northern China. *Catena* 206, 105528. doi:10.1016/j.catena.2021.105528

García-Rodeja, I., and Gil-Sotres, F. (1997). Prediction of Parameters Describing Phosphorus-Desorption Kinetics in Soils of Galicia (Northwest Spain). *J. Environ. Qual.* 26, 1363–1369. doi:10.2134/jeq1997.00472425002600050023x

García-Rodeja, E., Nóvoa-Muñoz, J. C., and Pontevedra-Pombal, X. (2023). "Soils of Galicia," in *The Environment in Galicia: A Book of Images. Galician Environment Through Images* (Cham: Springer International Publishing), 109–135.

Gruba, P., and Mulder, J. (2015). Tree Species Affect Cation Exchange Capacity (CEC) and Cation Binding Properties of Organic Matter in Acid Forest Soils. *Sci. Total Environ.* 511, 655–662. doi:10.1016/j.scitotenv.2015.01.013

Gui, H., Wang, J., Hu, M., Zhou, Z., and Wan, S. (2023). Impacts of Fire on Soil Respiration and Its Components: A Global meta-analysis. *Agric. For. Meteorology* 336, 109496. doi:10.1016/j.agrformet.2023.109496

Guitián Ojea, F., and Carballas, T. (1976). "Técnicas De Análisis De Suelos," in *Pico Sacro*.

Gupta, N., Gaurav, S. S., and Kumar, A. (2013). Molecular Basis of Aluminum Toxicity in Plants: A Review. *Am. J. Plant Sci.* 4, 21–37. doi:10.4236/ajps.2013.412A3004

Hartmann, M., Niklaus, P. A., Zimmermann, S., Schmutz, S., Kremer, J., Abarenkov, K., et al. (2014). Resistance and Resilience of the Forest Soil Microbiome to Logging-Associated Compaction. *ISME J.* 8, 226–244. doi:10.1038/ismej.2013.141

Hartmann, M., Brunner, I., Hagedorn, F., Bardgett, R. D., Stierli, B., Herzog, C., et al. (2017). A Decade of Irrigation Transforms the Soil Microbiome of a Semi-Arid Pine Forest. *Mol. Ecol.* 26, 1190–1206. doi:10.1111/mec.13995

Herron, N., Davis, R., and Jones, R. (2002). The Effects of Large-Scale Afforestation and Climate Change on Water Allocation in the Macquarie River Catchment, NSW, Australia. *J. Environ. Manag.* 65, 369–381. doi:10.1006/jema.2002.0562

Hibbard, K. A., Law, B. E., Reichstein, M., and Sulzman, J. (2005). An Analysis of Soil Respiration Across Northern Hemisphere Temperate Ecosystems. *Biogeochemistry* 73, 29–70. doi:10.1007/s10533-004-2946-0

Joly, F. X., Milcu, A., Scherer-Lorenzen, M., Jean, L. K., Bussotti, F., Dawud, S. M., et al. (2017). Tree Species Diversity Affects Decomposition Through Modified Micro-Environmental Conditions Across European Forests. *New Phytol.* 214, 1281–1293. doi:10.1111/nph.14452

Kamprath, E. (1970). Exchangeable Aluminum as a Criterion for Liming Leached Mineral Soils. *Soil Sci. Soc. Am. J.* 34, 252–254. doi:10.2136/sssaj1970.03615995003400020022x

Kinraide, T. B. (2003). Toxicity Factors in Acidic Forest Soils: Attempts to Evaluate Separately the Toxic Effects of Excessive Al_3^+ and H^+ and Insufficient Ca_2^+ and Mg^{2+} upon Root Elongation. *Eur. J. Soil Sci.* 54, 323–333. doi:10.1046/j.1365-2389.2003.00538.x

Kinraide, T. B., Pedler, J. F., and Parker, D. R. (2004). Relative Effectiveness of Calcium and Magnesium in the Alleviation of Rhizotoxicity in Wheat Induced by Copper, Zinc, Aluminum, Sodium, and Low Ph. *Plant Soil* 259, 201–208. doi:10.1023/b:plso.0000020972.18777.99

Kochian, L. V., Hoekenga, O. A., and Pineros, M. A. (2004). How Do Crop Plants Tolerate Acid Soils? Mechanisms of Aluminium Tolerance and Phosphorous Efficiency. *Annu. Rev. Plant Biol.* 55, 459–493. doi:10.1146/annurev.arplant.55.031903.141655

Liao, C., Luo, Y., Fang, C., Chen, J., and Li, B. (2012). The Effects of Plantation Practice on Soil Properties Based on the Comparison Between Natural and Planted Forests: A Meta-Analysis. *Glob. Ecol. Biogeogr.* 21, 318–327. doi:10.1111/j.1466-8238.2011.00690.x

Lombao, A., Barreiro, A., Carballas, T., Fontúrbel, M. T., Martín, A., Vega, J. A., et al. (2015). Changes in Soil Properties After a Wildfire in Fragas Do Eume Natural Park (Galicia, NW Spain). *Catena* 135, 409–418. doi:10.1016/j.catena.2014.08.007

Lucas-Borja, M. E., Hedo, J., Cerdá, A., Candel-Pérez, D., and Viñegla, B. (2016). Unravelling the Importance of Forest Age Stand and Forest Structure Driving Microbiological Soil Properties, Enzymatic Activities and Soil Nutrients Content in Mediterranean Spanish Black Pine (*Pinus nigra Ar. Ssp. Salzmannii*) Forest. *Sci. Total Environ.* 562, 145–154. doi:10.1016/j.scitotenv.2016.03.160

Lucas-Borja, M. E., Hedo de Santiago, J., Yang, Y., Shen, Y., and Candel-Pérez, D. (2019). Nutrient, Metal Contents and Microbiological Properties of Litter and Soil Along a Tree Age Gradient in Mediterranean Forest Ecosystems. *Sci. Total Environ.* 650, 749–758. doi:10.1016/j.scitotenv.2018.09.079

Macías, F. (1986). Materias Orixinais E Solos De Galiza. Cuad. Seminario De Sargadelos. *n°* 47, 47–79.

Macías, F., Calvo, R. M., García, C., García-Rodeja, E., and Silva, B. (1982). "El Material Original: Su Formación E Influencia En Las Propiedades De Los Suelos De Galicia," in *Anales De Edafología Y Agrobiología*, 1747–1768.

Mahía, J., Pérez-Ventura, L., Cabaneiro, A., and Díaz-Raviña, M. (2006). Soil Microbial Biomass Under Pine Forests of the Northern Spain: Influence of Stand Age, Site Quality and Parent Material. *Investig. Agrar. Sist. Recur. For.* 15, 152–159.

Matzner, E., and Ulrich, B. (1983). "The Turnover of Protons by Mineralization and Ion Uptake in a Beech (*Fagus silvatica*) and a Norway Spruce Ecosystem," in *Effects of Accumulation of Air Pollutants in Forest Ecosystems: Proceedings of a Workshop Held at Göttingen, West Germany, May 16-18* (Dordrecht: Springer Netherlands), 93–103.

Medeiros, P. L. D., Pimenta, A. S., Miranda, N. D. O., Melo, R. R. D., Amorim, J. D. S., and Azevedo, TKBD (2025). The Myth that Eucalyptus Trees Deplete Soil water-a Review. *Forests* 16, 423. doi:10.3390/f16030423

Mungai, N. W., and Motavalli, P. P. (2006). Litter Quality Effects on Soil Carbon and Nitrogen Dynamics in Temperate Alley Cropping Systems. *Appl. Soil Ecol.* 31, 32–42. doi:10.1016/j.apsoil.2005.04.009

Oliveira, F. C. C., Bacon, A. R., Fox, T. R., Jokela, E. J., Kane, M. B., Martin, T. A., et al. (2025). Do Soil Enzymes Respond to Silvicultural Management? *For. Ecol. Manag.* 585, 122651. doi:10.1016/j.foreco.2025.122651

Olsen, S. R., and Sommers, L. E. (1982). "Phosphorus," in *Methods of Soil Analysis. Part 2. Chemical and Microbiological Properties*. Editor A. L. Page (Madison, WI: Agronomy Monographs), 9.

Onet, A., Grenni, P., Onet, C., Stoian, V., and Crisan, V. (2025). Forest Soil Microbiomes: A Review of Key Research From 2003 to 2023. *Forests* 16, 148. doi:10.3390/f16010148

Pandey, D. N. (2002). Global Climate Change and Carbon Management in Multifunctional Forests. *Curr. Sci.* 83, 593–602.

Pathan, S. I., Žifčáková, L., Ceccherini, M. T., Pantani, O. L., Větrovský, T., and Baldrian, P. (2017). Seasonal Variation and Distribution of Total and Active Microbial Community of β-glucosidase Encoding Genes in Coniferous Forest Soil. *Soil Biol. Biochem.* 105, 71–80. doi:10.1016/j.soilbio.2016.11.003

Peech, L., Alexander, L. T., and Dean, L. A. (1947). *Methods of Soil Analysis for Soil-Fertility Investigations*. Washington D.C. USA: USDA Cir. N°, 757.

Pereira, J. A., Oliveira, I., Sousa, A., Valentão, P., Andrade, P. B., Ferreira, ICFR, et al. (2007). Walnut (*Juglans regia* L.) Leaves: Phenolic Compounds, Antibacterial Activity and Antioxidant Potential of Different Cultivars. *Food Chem. Toxicol.* 45, 2287–2295. doi:10.1016/j.fct.2007.06.004

Priha, O., and Smolander, A. (1999). Nitrogen Transformations in Soil Under *Pinus sylvestris, Picea Abies* and *Betula pendula* at Two Forest Sites. *Soil Biol. Biochem.* 31, 965–977. doi:10.1016/S0038-0717(99)00006-1

Raich, J. W., and Potter, C. S. (1995). Global Patterns of Carbon Dioxide Emissions from Soils. *Glob. Biogeochem. Cycles* 9, 23–36. doi:10.1029/94GB02723

Rawls, W. J., Pachepsky, Y. A., Ritchie, J. C., Sobecki, T. M. and Bloodworth, H. (2003). Effect of soil organic carbon on soil water retention. *Geoderma*, 116(1–2), 61–76.

Robinson, D. (2007). Implications of a Large Global Root Biomass for Carbon Sink Estimates and for Soil Carbon Dynamics. *Proc. R. Soc. B Biol. Sci.* 274, 2753–2759. doi:10.1098/rspb.2007.1012

Robinson, N., Harper, R. J., and Smettem, K. R. J. (2006). Soil Water Depletion by *Eucalyptus spp*. Integrated into Dryland Agricultural Systems. *Plant Soil* 286, 141–151. doi:10.1007/s11104-006-9032-4

Rocha, J. H. T., du Toit, B., and Gonçalves, JLDM (2019). Ca^{2+} and Mg^{2+} Nutrition and Its Application in Eucalyptus and Pinus Plantations. *For. Ecol. Manag.* 442, 63–78. doi:10.1016/j.foreco.2019.03.062

Rodríguez Guitián, M. A., and Ramil Rego, P. (2007). Clasificaciones Climáticas Aplicadas a Galicia: Revisión Desde Una Perspectiva Biogeográfica.

Rodríguez-Rodríguez, J. C., Fenton, N. J., Bergeron, Y., and Kembel, S. W. (2023). Soil and Tree Phyllosphere Microbial Communities Differ Between Coniferous and Broadleaf Deciduous Boreal Forests. *Plant Soil* 488, 233–253. doi:10.1007/s11104-023-05959-y

Ruiz-Chután, J. A., Kalousová, M., Lojka, B., Colocho-Hernández, S., Prado-Córdova, J. P., Montes, L., et al. (2025). Impacts of Habitat Fragmentation on the Genetic Diversity of the Endangered Guatemalan Fir (*Abies Guatemalensis* Rehder). *Genetica* 153, 8. doi:10.1007/s10709-024-00225-0

Salazar, S., Sánchez, L. E., Álvarez, J., Valverde, A., Galindo, P., Igual, J. M., et al. (2011). Correlation Among Soil Enzyme Activities Under Different Forest System Management Practices. *Ecol. Eng.* 37, 1123–1131. doi:10.1016/j.ecoleng.2011.02.007

Sawada, K., Inagaki, Y., Sugihara, S., Funakawa, S., Ritz, K., and Toyota, K. (2021). Impacts of Conversion From Natural Forest to Cedar Plantation on the Structure and Diversity of Root-Associated and Soil Microbial Communities. *Appl. Soil Ecol.* 167, 104027. doi:10.1016/j.apsoil.2021.104027

Špulák, O., Šach, F., and Kacálek, D. (2021). Topsoil Moisture Depletion and Recharge Below Young Norway Spruce, White Birch, and Treeless Gaps at a Mountain-Summit Site. *Forests* 12, 828. doi:10.3390/f12070828

Stott, D. E., Andrews, S. S., Liebig, M. A., Wienhold, B. J., and Karlen, D. L. (2010). Evaluation of β-Glucosidase Activity as a Soil Quality Indicator for the Soil Management Assessment Framework. *Soil Sci. Soc. Am. J.* 74, 107–119. doi:10.2136/sssaj2009.0029

Sui, X., Zeng, X., Li, M., Weng, X., Frey, B., Yang, L., et al. (2022). Influence of Different Vegetation Types on Soil Physicochemical Parameters and Fungal Communities. *Microorganisms* 10, 829. doi:10.3390/microorganisms10040829

Tan, K. H. (1986). *Soil Sampling, Preparation, and Analysis*. New York, USA: Marcel Dekker.

Tin, H. S., Palaniveloo, K., Anilik, J., Vickneswaran, M., Tashiro, Y., Vairappan, C. S., et al. (2018). Impact of Land-Use Change on Vertical Soil Bacterial Communities in Sabah. *Microb. Ecol.* 75, 459–467. doi:10.1007/s00248-017-1043-6

Tomé, M., Almeida, M. H., Barreiro, S., Branco, M. R., Deus, E., Pinto, G., et al. (2021). Opportunities and Challenges of Eucalyptus Plantations in Europe: The Iberian Peninsula Experience. *Eur. J. For. Res.* 140, 489–510. doi:10.1007/s10342-021-01358-z

van Breemen, N., Lundström, U. S., and Jongmans, A. G. (2000). Do Plants Drive Podzolization Via Rock-Eating Mycorrhizal Fungi? *Geoderma* 94, 163–171. doi:10.1016/S0016-7061(99)00050-6

van Dijk, AIJM, and Keenan, R. J. (2007). Planted Forests and Water in Perspective. *For. Ecol. Manag.* 251, 1–9. doi:10.1016/j.foreco.2007.06.010

van Nuland, M. E., Smith, D. P., Bhatnagar, J. M., Stefanski, A., Hobbie, S. E., Reich, P. B., et al. (2020). Warming and Disturbance Alter Soil Microbiome Diversity and Function in a Northern Forest Ecotone. *FEMS Microbiol. Ecol.* 96, fiaa108. doi:10.1093/FEMSEC/FIAA108

Wang, C., Xue, L., Dong, Y., Hou, L., Wei, Y., Chen, J., et al. (2019). Contrasting Effects of Chinese Fir Plantations of Different Stand Ages on Soil Enzyme Activities and Microbial Communities. *Forests* 10, 11. doi:10.3390/f10010011

Wang, Q., Xiao, J., Ding, J., Zou, T., Zhang, Z., Liu, Q., et al. (2021). Differences in Root Exudate Inputs and Rhizosphere Effects on Soil N Transformation Between Deciduous and Evergreen Trees. *Plant Soil* 458, 277–289. doi:10.1007/s11104-019-04156-0

Wang, Y., Chen, L., Xiang, W., Ouyang, S., Zhang, T., Zhang, X., et al. (2021). Forest Conversion to Plantations: A Meta-Analysis of Consequences for Soil and Microbial Properties and Functions. *Glob. Change Biol.* 27, 5643–5656. doi:10.1111/gcb.15835

Waymouth, V., Miller, R. E., Ede, F., Bissett, A., and Aponte, C. (2020). Variation in Soil Microbial Communities: Elucidating Relationships with Vegetation and Soil Properties, and Testing Sampling Effectiveness. *Plant Ecol.* 221, 837–851. doi:10.1007/s11258-020-01029-w

Widyati, E., Nuroniah, H. S., Tata, H. L., Mindawati, N., Lisnawati, Y., Darwo, A. L., et al. (2022). Soil Degradation due to Conversion from Natural to Plantation Forests in Indonesia. *Forests* 13, 1913. doi:10.3390/f13111913

WRB IUSS Working Group (2022). *World Reference Base for Soil Resources. International Soil Classification System for Naming Soils and Creating Legends for Soil Maps.* 4th ed. Vienna, Austria: International Union of Soil Sciences.

Xue, W., Zhang, W., and Chen, Y. (2023). Heavy Thinning Temporally Reduced Soil Carbon Storage by Intensifying Soil Microbial Phosphorus Limitation. *Plant Soil* 484, 33–48. doi:10.1007/s11104-022-05782-x

Zang, X., Liu, M., Fan, Y., Xu, J., and Li, H. (2018). The Structural and Functional Contributions of β-Glucosidase-Producing Microbial Communities to Cellulose Degradation in Composting. *Biotechnol. Biofuels* 11, 51. doi:10.1186/s13068-018-1045-8

Zhang, Y., Chen, L., Wu, Z., and Sun, C. (2011). Kinetic Parameters of Soil β-Glucosidase Response to Environmental Temperature and Moisture Regimes. *Rev. Bras. Ciência do Solo* 35, 1285–1291. doi:10.1590/S0100-06832011000400022

Zhang, Y., Zou, J., Meng, D., Dang, S., Zhou, J., Osborne, B., et al. (2020). Effect of Soil Microorganisms and Labile C Availability on Soil Respiration in Response to Litter Inputs in Forest Ecosystems: A Meta-Analysis. *Ecol. Evol.* 10, 13602–13612. doi:10.1002/ece3.6965

Zhao, X., Li, F., Zhang, W., Ai, Z., Shen, H., Liu, X., et al. (2016). Soil Respiration at Different Stand Ages (5, 10, and 20/30 Years) in Coniferous (*Pinus tabulaeformis* Carrière) and Deciduous (*Populus davidiana* Dode) Plantations in a Sandstorm Source Area. *Forests* 7, 153. doi:10.3390/f7080153

Zhou, Z., Zhang, Z., Zha, T., Luo, Z., Zheng, J., and Sun, O. J. (2013). Predicting Soil Respiration Using Carbon Stock in Roots, Litter and Soil Organic Matter in Forests of Loess Plateau in China. *Soil Biol. Biochem.* 57, 135–143. doi:10.1016/j.soilbio.2012.08.010

Zhou, L., Liu, S., Gu, Y., Wu, L., Hu, H. W., and He, J. Z. (2023). Fire Decreases Soil Respiration and Its Components in Terrestrial Ecosystems. *Funct. Ecol.* 37, 3124–3135. doi:10.1111/1365-2435.14443

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Soil in Art. Its Representation in Naturalistic Painting of the 17th and 19th Centuries

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Soil has rarely been represented as the central object in the art of painting. Its occasional presence on canvases appears to be accidental, not depicted for itself but as a subordinate element of the landscape. In pictorial works, it is more frequently shown on its surface and rarely seen in profile or with the details that interest soil scientists. However, exceptionally, certain pictorial works show striking images of the soil, even allowing us to recognize its horizons and other soil features, which can be interpreted with today's knowledge. In the history of Western art, we observe that this has occurred coinciding with the periods in which naturalistic landscape painting developed. At such times, artists more frequently left their studios to take sketches from nature and, occasionally, to execute complete works outdoors, capturing details of reality not perceived in other artistic periods, including subtle characteristics of the soil. This would first occur in the 17th century, in the landscape art that emerged in the Nordic countries, and particularly in Dutch painting. This would later occur in the 19th century, especially in the landscape painting movements manifested in the so-called English School, the Barbizon School, and the Hague School. This article identifies and justifies, in their historical and cultural context, the paintings and painters who, during these exceptional artistic periods, focused more specifically on the representation of the soil.

Keywords: soil art, soil culture, painting, landscape, naturalistic landscape painting

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INTRODUCTION

Soil provides a wide range of ecosystem services, as is now widely recognized. These include the traditionally valued services of providing food and fiber, as well as the performance of a wide variety of environmental functions, which have gained relevance in current public discourse. However, at the same time, they have played and continue to play an important role in other aspects that have been less considered, such as cultural aspects, whether aesthetic, spiritual, or other ethical and knowledge dimensions.

The appreciation of these cultural values of soil is still incipient and insufficiently explored. However, the need to enrich the view of soil with new perspectives is already being pointed out, while opening new frontiers for soil science. Expanding knowledge about soil through different visions would also serve, reciprocally, to attract the attention of a broader audience than the restricted one of soil scientists, and in general would allow for greater communication between soil scientists and society.

In this sense, for some time now, some soil scientists have paved the way for greater interaction with other areas of scientific, humanistic, and artistic culture (Jenny, 1968; Wessolek, 2002; Hartemink, 2009; Toland and Wessolek, 2010; Feller et al., 2010; 2015; Landa and Feller, 2010; Toland and Wolter, 2023;

Moscatelli and Marinari, 2024). Furthermore, creative methods have even been explored to develop this interdisciplinary dialogue in a practical way, particularly with art.

The art of painting, by offering a visual and eloquent representation, generally recognizable, allows us to interpret how the soil was once viewed. Therefore, to a certain extent, it can be useful as a documentary source and cultural indicator.

The soil was gradually represented in Western pictorial art, almost in parallel with the birth and evolution of the landscape in painting, whose origins can be traced back to the Middle Ages and the Renaissance, until its later full consecration, evolving under different pictorial styles. Consequently, the soil was observable in paintings long before the soil science was established as a scientific discipline, which has developed in just 150 years of history, taking Dokuchaev as its founding reference, commonly considered the father of pedology (Hartemink, 2009; Brevik and Hartemink, 2010; Díaz-Fierros, 2011).

However, in these ancient paintings, soil is never depicted as a central object in itself, but rather as a subordinate element of the landscape. Furthermore, its representation is rarely observed in the detail shown in other natural elements, such as rocks or vegetation, for example. At the same time, from the outset, most paintings show the soil only in its superficial features, and less frequently its profile is observable, making it impossible to view it in three dimensions, as studied by soil scientists.

The soil profile only becomes visible in paintings when it is exposed in slope cuts, along roadsides or on escarpments. Even so, the differentiation of horizons or other soil characteristics would rarely be observable without prior excavation of the profile, which is inconceivable in times long before the scientific observation and knowledge of the soil. However, exceptionally, some paintings show eloquent soil images with textures, colors, or chromatic combinations corresponding to soil features that can identified with today's knowledge.

In this paper, we examine how the soil has been viewed in the history of pictorial art within Western culture. At the same time, we discuss the social and cultural context in which these paintings are situated. We will focus in particular on the two periods in which we believe soil and landscape have been most faithfully represented pictorially. According to our hypothesis, this occurred in the 17th and 19th centuries, when naturalistic movements were particularly developing in art.

PREVIOUS STUDIES

The representation of soil in the history of Western pictorial art has attracted the recent interest of some authors, who have pointed to selected paintings they considered the most representative examples. A pioneer in addressing this issue was Hans Jenny, best known for having developed a formula for the combined action of the factors of soil formation (Jenny, 1941), who later published a brief history of soil in art, from medieval to contemporary times (Jenny, 1968).

More recent contributions by other authors, in addition to highlighting some early representations of soil in art, also examine its image in parallel with the development of soil science, reflected in textbooks and other publications, as well as the more recent use of soil as an artistic medium. Hartemink (2009), for example, in a historical review, refers to precursor paintings of soil as well as its first representations in scientific literature. He also refers to the appearance in the mid-1950s of colour diagrams of soil profiles, mainly water paintings, such as those published by Kubiena (1954). He points out how they would later be illustrated with photographs, initially in black and white, and from the 1960s/1970s also with colour photos; and finally he describes the use of earth as a medium for artistic performances at the present time.

Similarly, other authors review the historical representation of soil in art and science, and also show interest in certain proposals from contemporary art (Toland and Wessolek, 2010; Feller et al., 2010; 2015). In relation to this last aspect, the interest in creative modalities that emerged in the 1960s and 1970s, generally known as Land Art, Eco Art, etc., is noteworthy. In fact, some soil scientists have proposed classifying them as "Soil Art" (Wessolek, 2002; Toland and Wessolek, 2010). Even cinematic representations of soil have been reported (Landa, 2010; Ganga et al., 2023), adding to other varied and original forms of cultural interpretation of soil (Minami, 2009; Landa and Feller, 2010).

Likewise, in our own contributions, we have pointed out two paintings that represent the soil profile in a truly interesting way (Pérez Moreira, 2016). They correspond precisely to the two historical moments mentioned above in which naturalism triumphed in art. These paintings were included in the annual calendar published by the Spanish Society of Soil Science dedicated to soil and art (Sociedad Española de la Ciencia del Suelo, 2016; Mataix-Solera et al., 2017).

THE SOIL IN PRECURSOR PAINTINGS

Some pictorial antecedents show only the surface soil, sometimes showing the furrows in the earth, turned over by the plow during agricultural tasks. Early and well-known examples include, for example, a miniature from the "Calendiers" *Très Riches Heures du Duc de Berry* (1413–1416), mostly attributed to Pol de Limbourg,[1] as well as the painting *The Fall of Icarus* (c. 1558–1560) by Pieter Brueghel the Elder.[2]

Regarding the representation of the soil in depth, some pioneering paintings suggest the existence of the soil beneath the surface, without actually depicting the soil profile (Pächt, 1997). Prominent examples include the following paintings: *Last*

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[1] *Très Riches Heures du Duc de Berry* (1413–1416), largely attributed to Pol de Limbourg, Musée Condé, Chantilly, France.

[2] *The Fall of Icarus* (c. 1558–1560), Pieter Brueghel the Elder. Musées Royaux des Beaux-Arts de Belgique, Bruxelles, Belgique.

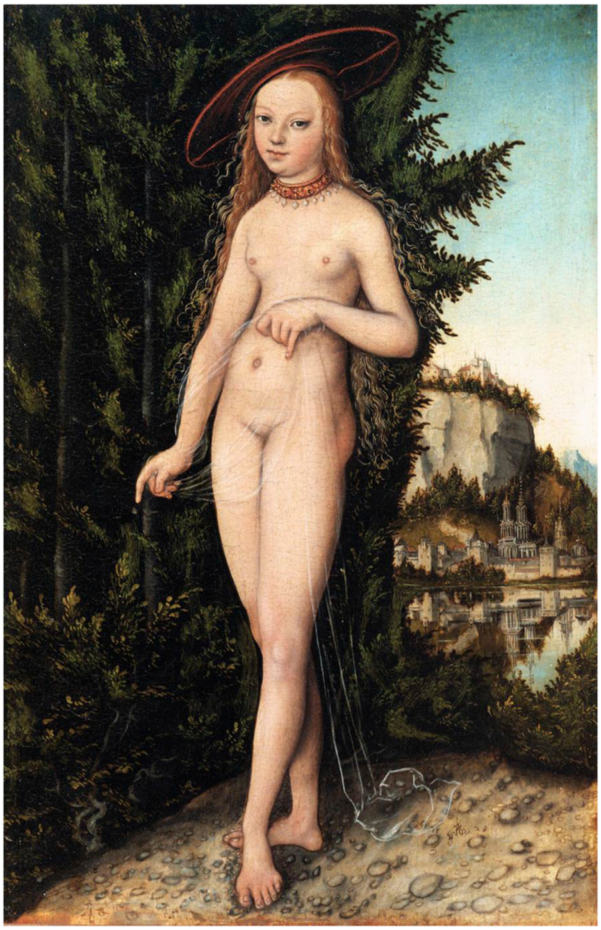

FIGURE 1 | Lucas Cranach the Elder, *Vénus debout dans un paysage* (c. 1529), Musée du Louvre. Paris, France. Image from: https://lucascranach.org/en/F_MdLP_1180/.

Judgment (c. 1443–1451) by Rogier van der Weyden;[3] *The Last Judgment* (c. 1466–1473) by Hans Memling;[4] *St. John the Baptist in the Wilderness* (c. 1489) by Hieronymus Bosch;[5] *Quattro allegorie-perseveranza* (c. 1490) by Giovanni Bellini;[6] *The Discovery of Honey by Bacchus* (c. 1499) by Piero di Cossimo;[7] *The Tempest* (c. 1508) by Giorgione;[8] *Vénus debout dans un paysage* (1529) by Lucas Cranach the Elder[9] (**Figure 1**). In some of such representations the soil has an essentially symbolic character, often lending itself to allegories alluding to the Resurrection of the dead, or serving as an excuse to display plant roots, also with a symbolic meaning (Feller et al., 2010; 2015).

FIGURE 2 | Giovanni Agostino da Lodi (Pseudo Boccaccino), *Pan y Siringa* (c.1510), Colección Thyssen-Bornemisza, Madrid, España. Image from: https://www.museothyssen.org/coleccion/artistas/lodi-giovanni-agostino-da/pan-siringa.

However, the soil profile is clearly observable in other early paintings. Good examples are the following: *Pan y Siringa* (c. 1510) by Giovanni Agostino da Lodi (Pseudo Boccaccino)[10] (**Figure 2**), active in Venice in the early 16th century, where a darkened horizon A is shown above the talus. Also in several works by Lodewijk de Vadder, a 17th-century Flemish painter, where a deep talus appears, showing reddish-brown or ochre soil tones, such as in *A Hilly Landscape with Travellers and a Wagon on a Path* (1640)[11] (**Figure 3**), in *Sunken Road with Figures in the Sonian forest* (c. 1640s-50s)[12] (**Figure 4**), or in *Landscape with Hunters* (1640s-50s)[13]. Likewise, even though no soil features are

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[3] *Last Judgment* (c. 1443–1451), Rogier van der Weyden, Musée Hôtel-Dieu, Beanne, France.

[4] *The Last Judgment* (c. 1466–1473), Hans Memling, National Museum of Gdansk, Poland.

[5] *St John Baptist in the Wildeners* (c. 1489), Hieronymus Bosch, Museo Lázaro Galdiano, Madrid.

[6] *Quattro Allegorie-perseveranza* (c. 1490), Giovanni Bellini, Gallerie Accademia, Venezia, Italia.

[7] *The Discovery of Honey by Bacchus* (c. 1499), Piero di Cossimo, Worcester Art Museum, Massachusetts, USA.

[8] *The Tempest* (c. 1508), Giorgione, Accademia di Belle Arti, Venezia, Italia.

[9] *Vénus debout dans un paysage* (c. 1529), Lucas Cranach the Elder, Musée du Louvre. Paris, France.

[10] *Pan y Siringa* (c. 1510), Giovanni Agostino da Lodi (Pseudo Boccaccino), Colección Thyssen-Bornemisza, Madrid, España.

[11] *A hilly landscape with travellers and a wagon on a path* (c. 1640), Lodewijk de Vadder, private collection (up for auction on 10/25/2017 in Bonhams, London).

[12] *Sunken Road with Figures in the Sonian forest* (1640-50), Lodewijk de Vadder, Museum of Fine Arts, Ghent, Belgium.

[13] *Paisaje con cazadores* (1640s-50s). Lodewijk de Vadder, Museo del Prado, Madrid, España.

FIGURE 3 | Lodewijk de Vadder, *A hilly landscape with travellers and a wagon on a path* (c. 1640), private collection (up for auction on 10/25/2017 in Bonhams, London). Image from: https://www.bonhams.com/auctions/24056/lot/228.

observed, an eloquent representation of the soil on its surface and in its profile, used in a precursory way as the main element that gives perspective to the painting, can be seen in *Country Road by a House* (1619–1620), by the German painter Goffredo Wals[14] (**Figure 5**).

THE SOIL IN 17TH-CENTURY NATURALISTIC PAINTING

Social and Artistic Context

There is an accepted consensus that the true birth of landscape in painting occurred at the beginning of the 17th century, in Nordic countries such as Germany and Flanders, and in a definitive way in Holland. Prior to this, there were gradual precedents, initially as a background or simple backdrop for figures. Later, the seemingly central subject became merely a pretext, minimized to magnify the Nature. For example, the landscape was already evident in works by artists such as Konrad Witz (1410–1445) or Joachim Patinir (1480/85–1525). Later, the landscape took on an independent role, devoid of figures, as it is demonstrated in some paintings by Albrecht Dürer (1471–1528), Albrecht Altdorfer (1480–1538), or Pieter Brueghel (1526/30–1569). However, it would not be until this significant moment in the 17th century when certain established criteria were fully met, to consider that the autonomous landscape truly emerged (Berque, 1995; 2009; Roger, 1997). This means that now the landscape is not only the prominent protagonist of the canvas but is an end in itself, not a simple stage subject to a story. Furthermore, it would coincide in time with the diffusion of the word "landscape" itself, which already emerged at the end of the 15th century (Maderuelo, 2006; Roger, 2008; López Silvestre, 2009; Pérez Moreira, 2010).

Historical reasons explain the triumph of the naturalistic landscape painting during the 17th century, which reached its zenith in its middle years, as the culminating artistic moment of what is commonly called the Golden Age of Dutch landscape painting. Political, economic, and religious changes occurred simultaneously. Their origin lay in the rebellion of the Netherlands against the Spanish monarchy, provoking a long war known as the Eighty Years' War (1568–1648). As early as 1579, the Seven United Provinces of the North (Holland) declared themselves an independent republic, separating themselves from the southern provinces (Flanders), which remained under the hegemony of the Spanish crown. The period of war concluded with the signing of the Treaty of Münster, by which Spain recognized the newly independent nation. At the same time, Protestantism replaced Catholicism in the religious dominance in this new nation. From then on, the new nation would experience immediate economic development, driven by a powerful commercial bourgeoisie, becoming one of the leading European powers of the time.

Regarding pictorial art, the traditional institutional and ecclesiastical patronage was lost. This was because in this new secularized and bourgeois society, both the courtly nobility and the Catholic Church ceased to be hegemonic. At the same time, the iconoclasm of the Reformed Church proscribed religious or mythological images, considering them idolatrous. This affected the traditional historical painting, which was restricted to the private sphere of the elite. The triumphant bourgeois class, with less cultural training and less interest in historical representations, appreciated new pictorial genres, including landscapes (Posada Kubissa, 2011).

The art of painting innovatively adapted to social changes (Brown, 1984; Franits, 2004). The new Dutch merchant bourgeoisie emerged as a class interested in owning paintings. A dynamic art market then flourished, becoming popular the small-format genre paintings, especially landscapes. Landscape paintings were collected by all classes of society, even the most modest, constituting almost 40% of artistic production by mid-century (Adams, 1994; Sutton, 1994). This could be partly explained by economic reasons derived from a special relationship with the land, significantly enlarged through the effort to drain wetlands, as in the regions surrounding Haarlem and Amsterdam (Adams, 1994). It could also be due to a certain nostalgia for the traditional rural landscape among a population that was now predominantly urban. But above all, it would be due to a civic pride in representing their free country, its joyful everyday reality, and its landscapes (Hauser, 1998; Adams, 1994; Sutton, 1994; Posada Kubissa, 2009). Landscape painting would therefore be a vehicle for affirming the new national identity.

Artists, in this early period, rarely painted outside their studios (Slive, 1995), but they frequently went into the field to take

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[14] *Country Road by a House* (1620s), Goffredo Wals, Kimbell Art Museum, Fort Worth, Texas, USA.

FIGURE 4 | Lodewijk de Vadder, *Sunken Road with Figures in the Sonian forest* (1640/50), Museum of Fine Arts, Ghent, Belgium. Image from: https://www.mskgent.be/en/collection/1938-a.

FIGURE 5 | Goffredo Wals, Country Road by a House (1620s). Image from: https://kimbellart.org/collection/ap-199102, Kimbell Art Museum, Fort Worth, Texas.

sketches from nature. These preliminary drawings would be used to create the final work, which was always executed back in their studio or workshop. However, by going outdoors to take sketches in the field, these painters captured details and subtleties previously unperceived, transcending traditional pictorial conventions. At the same time, these excursions allowed them to discover their nature and their country as a landscape.

The final artistic result was a peculiar naturalism in landscape painting, often interpreted as a true vision of its nature. Its apparent objectivity was based on a thorough representation of details. However, they painted scenes that were believable but not real, as they imaginatively reconstructed reality, translated in an exemplary manner. In truth, it was an idealized vision, in which imagination and convention combined with observation (Adams, 1994; Sutton, 1994; Slive, 1995).

This Dutch naturalistic landscape has also sometimes been attributed symbolic meanings, as concepts with moral undertones. However, today's dominant scholarly opinion questions this overinterpretation (Sutton, 1994; Alpers, 1987). Surely, there would be no other pretension than to mean the simple beauty represented in such landscapes.

The Pictorial Representation of the Soil

The soils of much of the Netherlands have mobile sand deposits as their parent material. These are frequently paleosols interbedded between successive sand layers. In these drifting sands, the youngest soils are little evolved; however, a study of the paleosols shows that most of them developed more or less evident podzolic characteristics (Koster, 2009; Sevink et al., 2023).

Some Dutch artists specialized in painting such dune landscapes, almost from the beginning and during the first half of the 17th century. In all these paintings, the human figure is subordinate, with the dunes as the main subject. One of the first to paint them, in a

FIGURE 6 | Jacob I. van Ruisdael, *Dunes* (c. 1650/53). Philadelphia Museum of Art, Pennsylvania, USA. Image from: https://philamuseum.org/collection/object/102356.

work dated 1614, was Esaias van de Velde (1587–1630), who was highly influential on later landscape artists (Sutton, 1994). Other artists also inspired by this subject were, mainly, Pieter van Santvoort (1604/05–1635), Jan J. van Goyen (1596–1656), Pieter de Molinj (1595–1661) and Salomon van Ruysdael (1600/03–1670). Likewise, these painters distinguished themselves among the creators of the so-called "tonal phase", toning the paintings in a unitary, almost monochromatic way, with a reduced palette of colors of warm tones, usually grays and earth tones (Sutton, 1994).

This group of artists laid the foundations for a subsequent "classical phase" of Dutch landscape painting, in which nature and landscape became monumentalized, with solid forms, accentuated contrasts, and more vivid colors (Sutton, 1994; Slive, 1995). These other painters were more versatile in their subjects, but they also represented dunes in their landscapes, either directly or in woodland or other scenes located on dune soils. Notable among these were Jacob I. van Ruisdael (1628/29–1682), Meinder Hobbema (1638–1709), and Philips Wouwerman (1619–1668), while the painter Jan Wijnants (1632/35–1684) stands out for having focused his entire artistic work on painting dunes and dune soils, as will be detailed later.

The soil profile is already hinted at in several of these dune paintings, at least with its A horizon clearly distinguishable. This surface horizon is observable, for example, in works by Aelbert Cuyp (1620–1691), such as in *A River Scene with Distant Windmills* (c. 1640-42),[15] as well as in *Wooded Landscape with an Artist* (c. 1643).[16] It is also present in various canvases by Jacob I. Van Ruisdael (1628–1682), an artist renowned for his meticulous depiction of natural elements, particularly his unmistakably recognizable trees. The soil can be seen in several of his works, such as in *Road through an Oak Forest* (c. 1646-47),[17] but more clearly in *Dunes* (c. 1650-53)[18] (**Figure 6**). The soil profile is much more eloquent in Salomon van Ruysdael's painting *Landscape with Sandy Road* (1628)[19], where an upper horizon with abundant roots stands out (**Figure 7**).

Jan Wijnants (Haarlem, 1632/35–Amsterdam, 1684) stands out not only for his exclusive specialization in dune paintings but also for his representation of distinct soil horizons. Like many other artists of the time, his thematic specialization was probably due to the demands of a market saturated with painters and paintings, which were quoted at very low prices, forcing them to focus on the topics in which they achieved greater recognition (Sutton, 1994; Slive, 1995).

This artist was inspired by the dunes near his native Haarlem. However, what is surprising is that his paintings with the most expressive soil horizons date from a period when he no longer lived there but in Amsterdam, where he would move permanently in December 1660. In paintings prior to this date, the soil profile is not clearly observed; however, in later works, the soil details are not merely anecdotal, but exceptional for their time and

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[15] *A River Scene with Distance Windmills* (c. 1640-42), Aelbert Cuyp, National Gallery, London, UK.

[16] *Wooded Landscape with an Artist* (c. 1643), Aelbert Cuyp, Wadsworth Atheneum Museum of Art, Hartford, USA.

[17] *Road through an Oak Forest* (1646-47), Jacob I. Van Ruisdael, Staten Museum for Kuns, Copenhagen, Denmark.

[18] *Dunes* (c. 1650/53). Jacob I. Van Ruisdael, Philadelphia Museum of Art, Pennsylvania, USA.

[19] *Landscape with Sandy Road* (1628), Salomon van Ruysdael, Norton Simon Museum, Pasadena, California, USA.

FIGURE 7 | Salomon van Ruysdael, *Landscape with Sandy Road* (1628), Norton Simon Museum, Pasadena, California, USA. Image from: https://www.nortonsimon.org/art/detail/F.1970.15.P/.

FIGURE 8 | Jan Wijnants, *Landscape with Hunters* (c. 1660-80), Cleveland Museum of Art, Ohio, USA. Image from: https://www.clevelandart.org/art/2011.48.

undoubtedly the result of prior observation, even though it later became a particular convention, repeated in varying degrees throughout his paintings.

In almost all of his paintings executed after 1660, the superficial A horizon can be clearly distinguished above the dune substrate, and in several of them podzolic soils can also

FIGURE 9 | Jan Wijnants, *Landschap met twee jagers* (1665–1684), Rijksmuseum, Amsterdam, The Netherlands. Image from: https://www.rijksmuseum.nl/en/collection/object/Landscape-with-two-Hunters–e3afc5e0ceb3f4f89930d90913809209?tab=data.

be distinguished, with a distinctive eluvial horizon (E) and even an underlying illuvial spodic B horizon (Bh, Bs). Among the best examples of this, the following works can be highlighted: *A wooded landscape with figures walking by a sandy bank* (1659-60),[20] perhaps the only one that could be done when he was still living in Haarlem; *A Track by a Dune, with Peasants and a Horseman* (c. 1655);[21] *Landscape with Hunters* (c. 1660-80)[22] (**Figure 8**) and *Landschap met twee jagers* (1665–1684)[23] (**Figure 9**). However, we consider that the most eloquent example of a soil profile, with features that can now be recognized as podzols, is observed in his painting *The Dunes near Haarlem* (1667)[24] (**Figure 10**).

THE SOIL IN 19TH-CENTURY NATURALISTIC PAINTING

Social and Artistic Context

Early 19th-century Europe emerged from successive wars and political turmoil in several countries, where an incipient Industrial Revolution was already emerging. England was at the forefront of progress, followed by France and the Netherlands, and then Germany. Industrial prosperity, above all, empowered a new bourgeoisie, wielding a power that until then had been held almost exclusively by monarchs and aristocrats (Pérez-Reverte, 2024).

Pictorial art, consequently, was no longer driven, as it once was, by the desire to express the grandeur of power, as expressed in traditional history paintings. This allowed artists to develop their individuality with fewer constraints (Hauser, 2003). Moreover, painters could not escape the new reality that manifested itself with the advances of progress over the course of the century. Nor will they be immune to the attraction aroused by scientific discoveries and the development of the natural sciences. Even some artists, along with poets, geographers, geologists, adventurers, etc., will participate in the intellectual atmosphere and desire for

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[20] *A wooded landscape with figures walking by a Sandy Bank* (1659-60), Jan Wijnants, Manchester Art Gallery, UK.

[21] *A Track by a Dune, with Peasants and a Horseman* (c. 1665), Jan Wijnants, National Gallery, London, UK.

[22] *Landscape with Hunters* (c. 1660-80), Jan Wijnants, Cleveland Museum of Art, Ohio, USA.

[23] *Landschap met twee jagers* (c. 1665–1684), Jan Wijnants, Rijksmuseum, Amsterdam, Netherlands.

[24] *The Dunes near Haarlem* (1667), Jan Wijnants, National Gallery of Ireland, Dublin.

FIGURE 10 | Jan Wijnants, *The Dunes near Haarlem* (1667), National Gallery of Ireland, Dublin. Image from: https://www.nationalgalleryimages.ie/search/?searchQuery=Jan+Wijnants%2C+The+Dunes+near+Haarlem, licensed under CC BY 4.0.

discovery of scientific excursionism, which will develop mainly at the end of the century. In this context, a certain convergence of scientific and humanistic cultures would occur, motivated by a shared interest in nature and the landscape (Pena, 1998; Casado de Otaola, 2010; Martinez de Pisón, 2017).

The great masters of the Golden Age of Dutch landscape painting exerted a notable influence on this 19th-century landscape painting, serving as inspiration for the resurgence of a new naturalism. Thus, for example, Thomas Gainsborough and John Constable, pioneers of this emerging trend, looked back and studied with devoted admiration the paintings of Ruisdael, Hobbema, and Wijnants, as did other painters involved in this artistic movement. It could therefore be argued that the most revolutionary and lasting contribution of the Dutch landscape painting precedent was its naturalism (Sutton, 1994). Thus, naturalism and the practice of outdoor painting are once again appreciated. Now artists will approach painting from nature in a more consistent manner, with *plein air* painting becoming a success.

In the preceding 18th century, the socio-historical circumstances and the prevailing aesthetic criteria were not conducive to an equivalent development of pictorial naturalism and plein-air painting. Both were disparaged even in their country of origin, declining there shortly after reaching their zenith, especially due to the subsequent artistic and normative expansion of French academicism (Pena, 2000; López-Manzanares, 2013).

Open-air painting was unusual, with a few exceptions. This was partly because it was not valued as a priority in the pictorial tradition. Likewise, landscape painting was still considered a minor genre in the pictorial hierarchy, secondary to history painting, which enjoyed the highest academic recognition. But it was also the case, especially with oil painting, that its execution in the field was technically complicated until certain technical innovations facilitated the task. Specifically, the invention of paint tubes and portable or field easels, in the mid-century, simplified fieldwork and led to the further development of this plein air activity (Graham-Dixon et al., 2020).

For some time now, highly influential treatises had dictated standards regarding landscape painting and open-air painting. Among the most famous were those written by Karol van Mander (published in 1604), Roger de Piles (published in 1708), and Pierre-Henri de Valenciennes (published in 1800), which remained reference texts for a long time. In all of them, the practice of painting from life was advocated, but solely for the purpose of acquiring a repertoire of notes with which to later compose the complete work, which invariably had to be developed in the studio (López-Manzanares, 2013; Pomarède, 2013). In other words, sketches that were simply copies from life were not yet considered true art, but rather what was subsequently recomposed and reinvented with them. What was valued as art was not imitation but creation, and not the landscape elements themselves, but their composition as an integral part of historical painting.

Another preliminary step on the path to the full triumph of pictorial naturalism was to overcome the sublime fantasies characteristic of Romanticism. At this earlier stage, nature was not yet an end but a means of expressing feelings. However, in their romantic exaltation, some artists elevated landscape painting to the level of recognition of historical painting. With them, the pictorial category of the "picturesque" would also be confirmed. In their struggle against the rules imposed on art, they anticipated "l'art pour l'art" (art for its own end), an art more free of prejudice, with its consequent freedoms for artistic development (Hauser, 2003).

After Romanticism's flight from reality, a return to it arose with Realism. The aim was no longer to create a breathtaking or picturesque setting, but rather to faithfully reproduce nature as it is, as a natural entity, of interest in itself. The theoretical discourse would also adjust to this shift in approach. For example, John Ruskin, in his monumental work *Modern Painters* (1843–1860), in his advice to young painters, specified that nature should be copied truthfully "in the best way of penetrating its meaning; without rejecting anything, without choosing anything and without despising anything" (Ruskin, 1848).

In contemporary naturalistic/realistic painting, work from life would no longer be secondary and subordinate to its completion in the studio, as had been the case until then. The balance nature-studio, as well as the gradation between faithful reproduction or the reproduction of one's own feelings, would depend on the will of each artist (López-Manzanares, 2013). Furthermore, in contrast to the academic postulates of the "universal" and the "ideal," in Realism the "local" and the "real" prevail (Pena, 2000). This painting demonstrates sincerity and meticulous attention to detail. In it, natural elements are no longer simply decorative elements of the composition, but are reproduced as singular entities and according to their own reality.

This new naturalistic landscape painting would develop in Europe mainly in three areas, which are now retrospectively referred to as the English School, the Barbizon School, and the Hague School.

The English School of landscape painters of the early 19th century was partly a Romantic expression, partly a transcendence of Romanticism, and the initiator of Naturalism (Hauser, 2003). Its landscape painters were pioneers in the practice of open-air painting. However, the opportunity for definitive academic recognition of the landscape genre and *plein ai*r painting arose in France with the creation in 1817 of the "Grand Prix de Rome de paysage historique", an award that included a coveted two-year pension in Rome (Pomarède, 2013). One of the most feared exercises was the "tree test," which required many of the candidates to practice painting studies in forests near the French capital, the most notable being the Forest of Fontainebleau.

The Barbizon School is the name given to the group of painters who came to this French village, about 50 km southeast of Paris, to find inspiration in the nearby Fontainebleau forest. This place would attract several generations of landscape artists to paint outdoors, primarily between 1820 and 1860 (Schama, 1999; Hauser, 2003; Oropesa and Caille, 2007; López-Manzanares, 2013; Schulman, 2013). However, they did not constitute a uniform movement or a shared ideal, having only in common a rejection of imposed academic rules and an enthusiasm for painting from nature (Hauser, 2003; Schulman, 2013).

The Hague School refers in turn to those painters who in Holland followed similar paths to those taken by the Barbizon artists, whose equivalent here would be the village of Oosterbeek, in the eastern part of the country. Many of the painters in this group were previously attracted to the Fontainebleau forest, and later developed their Dutch activity mainly between 1860 and 1885 (Suijver, 2009).

The Pictorial Representation of the Soil

In the English School of landscape painting, which had already emerged in the previous century, the view of the soil was anticipated in some paintings. The soil profile appears -although its horizons are not clearly defined- in several works by Thomas Gainsborough (1727–1788), such as *A View in Suffolk* (1746-47)[25] (**Figure 11**). However, it was the work of John Constable (1776–1837) that marked a substantial change from earlier landscape artists. He is considered one of the first artists to paint deliberately outdoors, having begun doing so in 1810 and continuing for most of his life. This painter was a pioneer in a period of transition between Romanticism and Realism, incorporating truth and emotion, although his painting was not an exact realism. The soil profile is clearly shown in several of his paintings, such as *Dedham Vale* (1802)[26] (**Figure 12**) or *Dell at Helmingham Park* (c. 1825-26),[27] in which the surface horizon and other soil features are distinguished. Another British painter of this period was J. M. William Turner (1775–1851), also ahead of his time, who himself would move away from figurative and realistic painting, dissolving forms and colors, and advancing the art of later times; the upper horizon of the soil is suggested in his work *The Bay of Baiae with Apollo and the Sibyl* (1823).[28]

In the Barbizon School, the painters who anticipated naturalistic landscape painting were Georges Michel (1763–1843) and Làzare Bruandet (1755–1804), who made their first field trips together to paint from life, doing so in places close to Paris. They also represented a turning point in landscape art, moving away from the idealist tradition of classicism, capturing in their paintings both reality and the artist's feelings. The soil is intuited in works by Georges Michel such as *Landschap met zandweg* (1820),[29] but the soil profile is more clearly seen in works by Làzare Bruandet -one of the first to visit the Fontainebleau Forest-, as in *Vue prise dans le forêt de Fontainebleau* (1785),[30] and in *Paysage avec chasseurs* (c. 1780-90),[31] where the upper horizon can be clearly distinguished.

The soil profile was eloquently represented in paintings by Jacques-Raymond Brascassat (1804–1867) and Jean Baptiste Camille Corot (1796–1875), who were also among the first

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[25] *A View in Suffolk* (1746-47), Thomas Gainsborough, National Gallery of Ireland, Dublin.

[26] *Dedham Vale* (1802), John Constable, Victoria and Albert Museum, London, UK.

[27] *The Dell at Helmingham Park* (1825-26), John Constable, Philadelphia Museum of Arts, USA.

[28] *The Bay of Baiae with Apollo and the Sibyl* (1823), J. M. William Turner, Tate Britain, London, UK.

[29] *Landschap met zandweg* (1820), Georges Michel, Museum Gouda, Netherlands.

[30] *Vue prise dans le forêt de Fontainebleau* (1785), Làzare Bruandet, Louvre Collections, on loan at Palaix du Luxenbourg-Sénat, Paris, France.

[31] *Paysage avec chasseurs* (c. 1780s-90s), Làzare Bruandet, Musée National Magnin, Dijon, France.

FIGURE 11 | Thomas Gainsborough, *A View in Suffolk* (1746-47), National Gallery of Ireland, Dublin. Image from: https://www.nationalgalleryimages.ie/search/?searchQuery=Thomas+Gainsborough%2C+A+View+in+Suffolk, licensed under CC BY 4.0.

FIGURE 12 | John Constable, *Dedham Vale* (1802), Victoria and Albert Museum, London, UK. Image from: https://collections.vam.ac.uk/item/O69881/dedham-vale-oil-painting-constable-john-ra/.

landscape artists to regularly visit the Fontainebleau Forest, back in the 1920s and early 1930s, and were the true precursors of the Barbizon School.

In Brascassat, the soil profile is evident in his painting *Rochers en forêt* (1828)[32] (**Figure 13**), which for a long time was considered to have been executed in the Fontainebleau forest, although this was not true. In fact, having been awarded second prize at the Grand Prix de Rome in 1825, he remained in Italy between 1826 and 1830, coinciding with the period in which he produced this painting, along with many others in which he depicted nature, composing paintings based on sketches taken from life. Another good example is seen in *Clairière en forêt* (1828).[33] Upon his return to Paris, he gained a reputation for animal paintings in which the soil profile is also visible in the foreground, such as *Un combat de taureau* (1855).[34]

In Corot, the truly realist intention is observed in his painting *Carrière de Chaise-Marie à Fontainebleau* (1831)[35] (**Figure 14**). It is a representation, not at all picturesque, of a fragment of nature that is interrupted by the frame of the painting, appearing to have been drawn directly from nature.

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[32] *Rochers en forêt* (1828), Jacques-Raymond Brascassat, Musée des Beaux-Arts de Reims, France.

[33] *Clairière en forêt* (1828), Jacques-Raymond Brascassat, Musée Paul-Dupuy, Toulouse, France.

[34] *Un combat de taureau* (1855). Jacques Raymond Brascassat, Musum of Fine Arts, Houston, Texas, USA.

[35] *Carrière de Chaise-Marie à Fontainebleau* (1831), Jean Baptiste Camille Corot, Musée des Beaux-Arts Gand, Belgique.

FIGURE 13 | Jacques-Raymond Brascassat, *Rochers en forêt* (1828), Musée des Beaux-Arts de Reims, France. Image from: https://musees-reims.fr/oeuvre/rochers-en-foret, by Christian Devleeschauwer, licensed under CC BY 2.0 FR.

This painting attests to the importance of the observation and truthful reproduction of nature, including the reproduction of the soil.

In the Hague School, we must highlight Willem Roelofs (1822–1897), one of its precursors and a leader of the movement in its early days. He was previously involved with the Barbizon School of Realists, visiting the Forest of Fontainebleau on three occasions. In his painting *Landschap bij naderend onweer* (1850)[36] (**Figure 15**), the soil appears to be part of an old riverbed, seen on its surface rather than in profile. Likewise, his painting *Forêt de Fontainebleau* (c. 1852-55)[37] is a good example of the realistic reproduction of details in this naturalistic art, with its meticulous representation of trees, rocks, and even soil.

As naturalism developed in the aforementioned English, Barbizon, and Hague schools, paintings in this style were also produced in other European countries. For example, in Spain, where the Belgian-born painter Carlos de Haes (1826–1898), would create a naturalist school of landscape at the Real Academia de Bellas Artes de San Fernando in Madrid, popularizing open-air painting and the faithful reproduction of natural reality (Pena, 1998; 2014; Gutiérrez Marquez, 2004; Casado de Otaola, 2010). Another example, also significant, is that of the Catalan landscape painter Joaquim Vayreda (1843–1894), who contributed to the founding of the renowned Olot School. Both artists, familiar with the pictorial work of Barbizon, suggest the vision of the soil in some of his paintings.

Finally, many of the painters who initially participated in this naturalistic art would later move toward other, less narrative and more informalist artistic styles. Among them were some of the best-known artists who practiced *plein-air* painting in the Fontainebleau forest. They initially evolved toward Impressionism, still a radically plein-air art, and later advanced toward other formulas, labeled as Symbolism, Fauvism, Expressionism, etc., in successive distortions on the path to abstraction and modernity (Thomson, 2014). To a certain extent, toward the end of the century, the prevailing naturalism was rejected in favor of new creative codes, no longer figurative but rather conceptual. Painters now sought to distinguish themselves with their own style that distanced themselves from the merely descriptive, replacing external reality with one born from the artist's spirit. Consequently, under these new aesthetic parameters, the faithful reproduction of nature loses interest, while the soil profile would no longer be represented in a recognizable and realistic way.

CONCLUSION

Soil is very rarely represented explicitly and for itself in the history of painting. However, exceptionally, some early paintings already show soil horizons and soil features in

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[36] *Landschap bij naderend onweer* (1850), Willem Roelofs, Rijksmuseum, Amsterdam, Netherlands.

[37] *Forêt de Fontainebleau* (c. 1852-55), Willem Roelofs, Museum Boijmans Van Beuningen, Rotterdam, Netherlands.

FIGURE 14 | Jean Baptiste Camille Corot, *Carrière de Chaise-Marie à Fontainebleau* (1831), Musée des Beaux-Arts Gand, Belgique. Image from: https://www.mskgent.be/fr/collection/1914-di.

FIGURE 15 | Willem Roelofs, *Landschap bij naderend onweer* (1850), Rijksmuseum, Amsterdam, The Netherlands. Image from: https://www.rijksmuseum.nl/nl/collectie/object/Landschap-bij-naderend-onweer–525e62041874927f3ac3c5ed30ef0523.

some detail, which we can even identify with today’s knowledge.

This work shows that the most eloquent pictorial representations of the soil emerge, in Western art, at the same time as the development of naturalistic currents in landscape painting, as occurred primarily during the 17th and 19th centuries, due to exceptional circumstances that favored the open-air pictorial exercise. This allowed painters to perceive subtleties of Nature and landscape not observed with equal precision in other artistic periods. However, from the end of the 17th century and throughout the 18th century, the socio-historical context and the prevailing aesthetic criteria were not equally conducive to an equivalent development of pictorial naturalism and plein-air painting.

The pictorial representation of soil is especially notable in those two aforementioned periods. Particularly noteworthy are works from 17th-century Dutch painting, as well as from the

English, Barbizon, and Hague schools, developed in the 19th century. This pictorial exceptionality is justified by the social and cultural context that have been discussed, pointing out the historical conditions and aesthetic codes under which these artistic works were created.

Finally, as a complementary reflection to this study, we consider that the art of painting offers interesting new aspects regarding soil. On the one hand, its pictorial image can serve as a documentary source and cultural indicator, testifying to how soil was viewed in earlier historical periods, prior to the birth of soil science. On the other hand, pictorial art can help provide an attractive image of soil for both the public and soil scientists themselves. Artistic representations of the soil, in their various forms, both figurative art and other innovative forms experimented with in contemporary art, contribute to its dissemination and greater awareness by society. At the same time, it can favor a beneficial interdisciplinary approach between scientific and humanistic fields, even collaborating with artists and educators, thus opening up new opportunities for soil science.

DATA AVAILABILITY STATEMENT

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

AUTHOR CONTRIBUTIONS

RP conceptualized the work, carried out the bibliographic review and contributed to the writing of the text. MB participated in the selection of the more representative paintings and contributed to the writing of the text. All authors contributed to the article and approved the submitted version.

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REFERENCES

Adams, A. J. (1994). "Competing Communities in the «Great Bog of Europe». Identity and Seventeenth-Century Dutch Landscape Painting," in *Landscape and Power*. Editor W. J. T. Mitchell (Chicago and London: The University of Chicago Press), 35–76.

Alpers, S. (1987). "Introducción" and "Apéndice", *in El arte de describir: el arte holandés del siglo XVII*. Madrid: Hermann Blume, 17-31 and 311–316.

Berque, A. (1995). *Les Raisons du paysage*: *De la Chine antique aux environnements de synthése* (París: Hazan), 192.

Berque, A. (2009). in *El Pensamiento Paisajero*. Editor J. Maderuelo (Madrid: Biblioteca Nueva), 144.

Brevik, E. C., and Hartemink, A. E. (2010). Early Soil Knowledge and the Birth and Development of Soil Science. *Catena* 83 (1), 23–33. doi:10.1016/j.catena.2010.06.011

Brown, C. (1984). *Scenes of Everyday Life. Dutch Genre Painting of the Seventeenth Century*. London: Faber and Faber, 240.

Casado de Otaola, S. (2010). *Naturaleza patria. Ciencia y sentimiento de la naturaleza en la España del regeneracionismo*. Madrid: Marcial Pons Ediciones de Historia, 379.

Díaz-Fierros, F. (2011). *La ciencia del suelo. Historia, concepto y método*. Santiago de Compostela: Univ. Santiago de Compostela, 191.

Feller, C., Chapuis-Lardy, L., and Ugolini, F. (2010). "The Representation of Soil in the Western Art: From Genesis to Pedogenesis," in *Soil and Culture*. Editors E. R. Landa and C. Feller (Dordrecht: Springer), 3–22.

Feller, C., Landa, E. R., Toland, A., and Wessolek, G. (2015). Case Studies of Soil in Art. *Soil* 1 (2), 543–559. doi:10.5194/soil-1-543-2015

Franits, W. (2004). *Dutch Seventeenth-Century Genre Painting. Its Stylistic and Thematic Evolution*. New Haven and London: Yale University Press, 328.

Ganga, A., Ribeiro, L., Paganini, E. A., Dilipkumar, A., Abreu-Junior, C. H., Nogueira, T. A. R., et al. (2023). Filming a Hidden Resource: The Soil in Seventh Art Narrative. *Geoderma* 440, 1–12. doi:10.1016/j.geoderma.2023.116710

Graham-Dixon, A., Braine, A., Bray, G., Chilves, I., Gwynne, P., Zaczek, L., et al. (2020). *Historia de la pintura. Cómo Se Hizo Arte* (Madrid: Akal), 360.

Gutiérrez Marquez, A. (2004). *Carlos de Haes en el Museo del Prado. Catálogo razonado. Exposición 2004-2005.* (A Coruña: Museo de Belas Artes da Coruña), 422.

Hartemink, A. E. (2009). The Depiction of Soil Profiles since the Late 1700s. *Catena* 79 (2), 113–127. doi:10.1016/j.catena.2009.06.002

Hauser, A. (1998). *Historia social de la literatura y el arte. I: Desde la Prehistoria hasta el Barroco*. Madrid: Debate, 567.

Hauser, A. (2003). *Historia social de la literatura y el arte. II: Desde el Rococó hasta la época del cine*. Madrid: Debate, 539.

Jenny, H. (1941). *Factors of Soil Formation. A System of Quantitative Pedology*. New York: McGraw-Hill, 281.

Jenny, H. (1968). "The Image of Soil in Landscape Art, Old and New," in *Organic Matter and Soil Fertility* (Città del Vaticano: Pontificiae Academia Scientarium. Scripta Varia), 979–1011.

Koster, E. A. (2009). The "European Aeolian Sand Belt". Geoconservation of Drift Sand Landscapes. *Geoheritage* 1 (1), 93–110. doi:10.1007/s12371-009-0007-8

Kubiena, W. L. (1954). *Atlas de perfiles de suelos* (Madrid: Inst. de Edafología y Fisiología Vegetal, CSIC), 28.

Landa, E. R. (2010). "In a Supporting Role: Soil and the Cinema," in *Soil and Culture*. Editors E. R. Landa and C. Feller (Dordrecht: Springer), 83–105.

Landa, E. R., and Feller, C. (2010). *Soil and Culture* (Dordrecht: Springer), 488.

López-Manzanares, J. A. (2013). "Al Aire Libre," *in Impresionismo y aire libre, de Corot a Van Gogh* (Madrid: Fundación Colecc. Thyssen-Bornemisza), 13–33.

López-Silvestre, F. (2009). "Cara a unha teoría integral da paisaxe," in *Olladas críticas sobre a paisaxe*. Editors F. Díaz-Fierros and F. López-Silvestre (Santiago de Compostela: Consello da Cultura Galega), 93–104.

Maderuelo, J. (2006). *El paisaje, génesis de un concepto* (Madrid: Abada), 344.

Martinez de Pisón, E. (2017). *La Montaña Y El Arte. Miradas desde la pintura, la música y la literatura* (Madrid: Fórola Ediciones), 614.

Mataix-Solera, J., Poch, R. M., Díaz-Fierros, F., Pérez-Moreira, R., Asins, S., Porta, J., et al. (2017). Soil and Art: The Spanish Society of Soil Science Calendar for 2016. *Geophys. Res. Abstr.* 19. Available online at: https://meetingorganizer.copernicus.org/EGU2017/EGU2017-203.pdf (Accessed July 28, 2025).

Minami, K. (2009). Soil and Humanity: Culture, Civilization, Livelihood and Health. *Soil Sci. Nutr.* 55, 603–615. doi:10.1111/j.1747-0765.2009.00401.x

Moscatelli, M. C., and Marinari, S. (2024). Digging in the Dirt: Searching for Effective Tools and Languages to Promote Soil Awareness. *Soil Secur.* 16, 100167. doi:10.1016/j.soisec.2024.100167

Oropesa, M., and Caille, M. T. (2007). *La Escuela de Barbizón. Catálogo Exposición* (Vigo: Centro Cultural Caixanova), 95.

Pächt, O. (1997). *Early Netherlandish Painting. From Rogier van der Weyden to Gerard David*. Editor M. Rosenauer (London: Harvey Miller Publishers), 264.

Pena, C. (1998). *Pintura de paisaje e ideología. La generación del 98* (Madrid: Taurus), 170.

Pena, C. (2000). "Aspectos da tradición do pintoresco na Colección Carmen Thyssen-Bornemisza," in *Texto do Catálogo da Exposición: De Van Goyen a Constable. Aspectos da tradición do pintoresco na Colección Carmen Thyssen-Bornemisza* (A Coruña: Museo de Belas Artes da Coruña), 221.

Pena, C. (2014). "La invención del paisaje español," in *Del realismo al impresionismo* (Madrid: Círculo de Lectores: Galaxia Gutenberg), 143–165.

Pérez Moreira, R. (2010). "A descuberta cultural da paisaxe," in *Cultura e Paisaxe*. Editors R. Pérez Moreira and F. J. López González (Santiago de Compostela: Universidade de Santiago de Compostela), 19–51.

Pérez Moreira, R. (2016). "Wijnants, Dunas cerca de Haarlem (1667); Raymond Brascassat, Peñascos en el bosque (1828)," in *Suelos Y Arte. Calendario SECS (April, Wijnants; Back Cover, Brascassat)* (Madrid: Sociedad Española de la Ciencia del Suelo).

Pérez-Reverte, A. (2024). "Una Historia de Europa (LXXXVI)," in *XL-semanal*, 11-VIII-2024.

Pomarède, V. (2013). "Pierre-Henri de Valenciennes y los ornamentos de la naturaleza," in *Impresionismo y aire libre, de Corot a Van Gogh* (Madrid: Fundación Colección Thyssen-Bornemisza), 35–47.

Posada Kubissa, T. (2009). *Pintura holandesa en el Museo Nacional del Prado*. Catálogo de la Colección (Madrid: Museo Nacional del Prado), 336.

Posada Kubissa, T. (2011). "Rubens, Brueghel, Lorena. El paisaje nórdico en el Prado," in *Catálogo de la Colección* (Madrid: Museo Nacional del Prado), 181.

Roger, A. (1997). *Court traitè du paysage* (París: Gallimard). Spanish translation, 2007: *Breve tratado del paisaje.* (Madrid: Biblioteca Nueva), 236.

Roger, A. (2008). "Vida y muerte de los paisajes. Valores estéticos, valores ecológicos," in *El paisaje en la cultura contemporánea*. Editor J. Nogué (Madrid: Biblioteca Nueva), 67–85.

Ruskin, J. (1848). *Modern Painters*. 4th Edn. (London: Smith, Elder and Co.).

Schama, S. (1999). *Le Paysage et la Mémoire*. Paris: Editions du Seuil, 720.

Schulman, M. (2013). "La pintura al aire libre en la Escuela de Barbizón," in *Impresionismo y aire libre, de Corot a Van Gogh* (Madrid: Fundación Colección Thyssen-Bornemisza), 49–59.

Sevink, J., Wallinga, J., Reiman, T., Van Geel, B., Brinkkemper, O., Jansen, B., et al. (2023). A Multi-Staged Driff Sand Geo-Archive from the Netherlands: New Evidence for the Impact of Prehistoric Land Use on the Geomorphic Stability, Soils, and Vegetation of Aeolian Sand Landscapes. *Catena* 224, 1–17. doi:10.1016/j.catena.2023.106969

Slive, S. (1995). *Dutch Painting, 1600-1800*. New Haven: Yale University Press, 365.

Sociedad Española de la Ciencia del Suelo (SECS) (2016). *Suelos y Arte. Calendario SECS* (Madrid, Sociedad Española de la Ciencia del Suelo).

Suijver, R. (2009). "Reflexos da paisaxe holandesa. A pintura da Escola da Haia", in *La Escuela de la Haya. Obras maestras del Rijksmuseum*. (Amsterdam: Rijksmuseum, and Vigo: Fundación Caixanova), 17–37.

Sutton, P. C. (1994). "Introducción," in *El Siglo de Oro del paisaje holandés. Catálogo de Exposición (Authors P. C. Sutton with the collaboration of J. Loughman)* (Madrid: Fundación Colección Thyssen-Bornemisza), 15–57.

Thomson, R. (2014). "El caso del «postimpresionismo»: La búsqueda de estilo y el fracaso de una etiqueta estilística," in *Del realismo al impresionismo* (Madrid: Círculo de Lectores: Galaxia Gutenberg), 267–287.

Toland, A. R., and Wessolek, G. (2010). "Merging Horizons – Soil Science and Soil Art," in *Soil and Culture*. Editors E. R. Landa and C. Feller (Dordrecht: Springer), 45–66.

Toland, A. R., and Wolter, D. (2023). "Soil Art: Sensory and Symbolic Engagement with Soils," in *Enciclopedia of Soils in the Environment*. Editors M. J. Goos and M. Oliver (Amsterdam: Elsevier), 509–520.

Wessolek, G. (2002). *Art and Soil: Newsletter 10* (Rome: The Committee on the History, Philosophy, and Sociology of Soil Science International Union of Soil Science, and Madison: Council on the History, Philosophy, and Sociology of the Soil Science Society of America), 14–15.

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Proficiency Testing for Soil Fertility Analysis

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In the context of the FAO Global Soil Partnership, the Spanish Society of Soil Science (Sociedad Española de la Ciencia del Suelo, SECS), the University of Zaragoza and the Agroenvironmental Laboratory of the Government of Aragon promoted initiatives for the harmonization of soil analysis methods in Spain. These included the development of an inventory of laboratories and the organization of proficiency tests of soil analytical results. The first test, carried out in 2019, showed significant discrepancies among laboratories, which led to methodological improvements for the second test in 2021. Twenty-six laboratories participated in the latter test, evaluating soil fertility parameters (organic matter, assimilable phosphorus, potassium and magnesium) and textural fractions (clay and sand). The analyses, carried out in triplicate, were evaluated using robust statistics and Zscore. The 2021 results showed that sample 'HUERTO' had a higher percentage of satisfactory results than "BIPEA," mainly due to its greater standard deviation. The assessment identified problems arising from differences in analytical methods, especially for organic matter. A comparison of the two exercises revealed that, out of 17 laboratories analyzed, 10 improved their overall performance, 3 maintained it and 4 deteriorated. A positive trend was observed for assimilable phosphorus and magnesium, parameters that achieved satisfactory overall ratings, while sand and organic matter content showed more problematic results. Despite the improvements observed, only five out of the seventeen laboratories achieved an overall satisfactory rating, which underlines the need to regularly maintain and strengthen these proficiency tests. These results are particularly relevant within the context of the CAP Strategic Plan, which requires reliable data on the state of agricultural soils. This exercise has proven to be an effective tool for encouraging continuous improvement in the analytical quality of soil laboratories, contributing to the sustainable governance of soil resources.

Keywords: organic matter, phosphorus, potassium, magnesium, soil laboratories

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INTRODUCTION

In December 2012, the Food and Agriculture Organization of the United Nations (FAO) established the Global Soil Partnership (Soil Partnership), with the main objective of improving the governance and sustainable management of soils. This Soil Partnership has five pillars, the fifth of which seeks to harmonize methods, measures and indicators for the sustainable management and protection of soil resources. Within this framework, technical networks were created, including "The Global Soil Laboratory Network" (GLOSOLAN) which was established at an FAO meeting at its headquarters in

Rome, in November 2017 to strengthen the capabilities of soil testing laboratories and respond to the need to harmonize soil testing results.

In Spain, the Spanish Society of Soil Science (Sociedad Española de la Ciencia del Suelo, SECS) together with the University of Zaragoza and the Agroenvironmental Laboratory (of the Government of Aragon), adopted the GLOSOLAN initiative and initiated the development of two fundamental activities:

- An inventory of laboratories performing soil analysis
- A proficiency test to assess the homogeneity of analysis results and facilitate improvements.

Jaime Porta played a crucial role in the development of soil analysis in Spain. As president of the SECS, he championed the Plant Fertility and Nutrition Section. On 10 April 2019 he inaugurated a meeting in Madrid to share the results of the first intercomparison exercise, which was sponsored by the Ministry of Agriculture, Fisheries and Food. Porta began his career as an engineer in the State Agricultural Laboratory Network (LAR), which he referred to as the García Faure project. In 1972, he became the head of the LAR in Galicia, where he established a soil laboratory. He then moved to the LAR of Ebro, where he was tasked with automating soil analysis. To prepare for this, he was sent by Rafael García Faure to study the automated systems at the INRA laboratory in Arras, France, and the Oosterberg cooperative laboratory in the Netherlands. After his time in Zaragoza, he worked at the LAR in Madrid until late 1977, when he left to join the university. Porta's tenure at the Ebro LAR, now the Agroenvironmental Laboratory of the Government of Aragon, had a lasting impact on the automation of soil analysis. He implemented several "Technicon" devices, which are comparable to modern segmented continuous flow systems, for the serial determination of phosphorus and soil organic matter. He also installed two pieces of "Granulostas" equipment (which have no modern equivalent) in a specialized room, enabling the lab to analyze approximately 100 soil textures per week. Porta's most significant contribution was in the field of quality control, as he anticipated the first laboratory quality protocols by two decades. He introduced several key practices, such as working in batches with multiple internal quality controls and establishing sample exchange networks. Porta was also a founding member of the "soils working group" within the Commission of Official Methods of Analysis of Spain, which was responsible for developing and drafting methods for agricultural analysis.

These official and obligatory methods have been used in the agricultural laboratories that depend on the Ministry. They constitute a fundamental tool for harmonizing the results of the analyses and making them interoperable. These official methods began to be published in 1976 (BOE, 1975), with several subsequent editions, the last of which appeared in 1994 (Ministerio de Agricultura, 1994). The official methods remained in that Commission until the end of the 1990s, when, after the transfers to the Autonomous Regions and the incorporation into the European Economic Community, interest in soil analysis declined, and the Commission ceased to act.

Following this new impetus, Order APA/1044/2024 of 23 September 2024 was published on 1 October 2024, designating the Agroenvironmental Laboratory of the Government of Aragon as the national reference laboratory for agricultural soil fertility analysis ("BOE no 237, 2024). In addition, an inventory of soil analysis laboratories is available (SECS, 2018) and two proficiency tests have been carried out to date, which are the focus of this work.

The first test, carried out in 2019, made it possible to fine-tune the methodology (Usón and Betrán, 2020) and revealed the urgent need to standardize procedures and results. The conclusions also led to the proposal of some modifications for subsequent exercises, such as:

- The reduction of the parameters to be analyzed. Since the majority of the intercomparison exercises carried out are limited to one or a few parameters (Bierer et al., 2021; Buczko et al., 2024; Kweon et al., 2015). The new studies focus on soil fertility and eliminate parameters with low response rates (such as carbonates, water retention and micronutrients).
- The introduction of intra-laboratory replicates to also characterize this variability (Guerrero and Bertsch, 2020).

The second test, completed in June 2022, focused on soil texture parameters, with three granulometric fractions, and optionally silt, which was separated into coarse and fine. The test also examined the main soil fertility parameters: organic matter, mineral nitrogen, assimilable phosphorus, potassium and magnesium. The results obtained by the laboratory were requested in three independent replicates (reproducibility conditions) for each parameter.

With these considerations in mind, the objective of this work is twofold. On the one hand, it aims to analyze the degree of homogeneity in soil fertility analysis results from different laboratories in the most recent year, 2021. Second, it seeks to evaluate the analytical consistency among laboratories in Spain with respect to six key soil fertility parameters in the years 2019 and 2021, and to detect trends of improvement or regression in their performance.

MATERIALS AND METHODS

For both the 2019 and 2021 proficiency tests, two agricultural soil samples were prepared with the standard soil procedure of drying, disaggregation and sieving at 2 mm. The samples were prepared in bulk and homogenized. The results of the first exercise have already been published (Usón and Betrán, 2020) so only the development of the 2021 exercise is described in detail here.

For the second test, the samples were named "BIPEA" and "HUERTO." In the first case it is a sample that was previously provided to the French organizer by that name, and prepared by them; in the second case, the sample was prepared directly by this organization. In both cases, the samples were taken from the superficial horizon (30 cm) of a cultivated soil.

Aliquots of both samples (approximately 500 g) were sent to a total of 29 Spanish laboratories that had shown interest in participating in the exercise. A total of 26 responded; 17 of them had already participated in the first test, and it is with these laboratories that the comparison was made.

TABLE 1 | Parameters for which analysis was requested from the participating laboratories, units in which to express the results, and the proposed reference method according to Spanish official soil analysis methods (BOE, 1975).

Parameters to be analyzed			
Determination	**Units/method**	**Determination**	**Units/method**
Organic matter	g/100 g Walkley-Black	Granulometry	
Nitrates (N-NO3)	mg/kg (N) UV spectrophotometry	Clay (<0.002 mm)	g/100 g Discontinuous sedimentation
Assimilable phosphorus	mg/kg (P) P Olsen	Fine silt (0.002–0.020 mm)	
Assimilable potassium	mg/kg (K) Cation exchange	Coarse silt (0.020–0.050 mm)	
Assimilable magnesium	mg/kg (Mg) Cation exchange	Sand (>0.050 mm)	g/100 g Gravimetric analysis

Following the WEPAL methodology (WEPAL, 2024), at the same time the sample was sent, each laboratory was provided with an Excel sheet for submitting the results. This Excel sheet specified both the units of measurement and the number of significant figures for the results. In order to maintain confidentiality regarding the origin of the results, which is an essential aspect, the code with the number of the sample sent was only known by the laboratory involved and by the two persons responsible for the organization of the exercise. The code for each Laboratory was a number ranging from 11 to 301.

An analytical profile focused on soil fertility and textural fractions was requested (**Table 1**) and the need to perform the analyses in triplicate, if possible in different batches, and to send the results of the 3 replicates was emphasized.

The received results were not modified in any way, and were treated statistically for each parameter.

A robust statistical analysis was used for the evaluation of the results (Laso Sánchez and García-Patrón Peris, 2009a; Laso Sánchez and García-Patrón Peris, 2009b). This analysis consisted of calculating the median and deviation from the median, and eliminating anomalous data through necessary iterations to finally obtain a mean and "consensus" standard deviation with the accepted values. The acceptance interval was calculated symmetrically from the latter values with a 95% confidence level.

The Zscore estimator was developed to assess the distance of each result from the consensus value, in terms of standard deviation:

$$Zscore = \frac{V_{lab} - V_{cons}}{\sigma_{cons}}$$

Where:

V_{lab} = Value of the laboratory.

V_{cons} = Consensus value (average of accepted values).

σ_{cons} = Consensus standard deviation (among accepted values).

The interpretation of the Zscore results is as follows:

- $Zscore \leq 2; Satisfactory$
  This interval includes, with a probability of 95%, all correct scores for that property.
- $2 \leq Zscore \leq 3; Questionable$
  There is a 5% probability that scores with this value belong to the population of correct property scores.
- $Zscore \geq 3; Unsatisfactory$
  A score with this value is highly unlikely to belong to the population of correct property scores.

Finally, as a tool for comparison, a "combined Zscore was calculated for both the set of results issued by each laboratory for each parameter and for all the results issued by each laboratory.

$$ZsC = \sqrt{\frac{\sum Zscore^2}{n}}$$

Where:

ZsC = combined Zscore.

n = number of results issued.

Finally, the results of the two tests were compared for the organic matter content, assimilable potassium, assimilable phosphorus, assimilable magnesium and for the sand and clay textural fractions. The procedure was as follows:

- A new code was assigned to each laboratory from 1 to 17; in this case, the codes were the same for both years, and the distribution of the ZsC data for each year was analyzed.
- Subsequently, the distribution of the data was analyzed and, since these did not follow a normal distribution, a logarithmic transformation was performed to normalize them. Then, two analyses of variance were performed:
  ○First, a one-factor ANOVA was analyzed for each laboratory, with the independent variable being the year in which the analyses were carried out.
  ○The second analysis used a one-factor ANOVA for each parameter with the same independent variable: the year in which the analyses were carried out.

RESULTS AND DISCUSSION

Results for the 2021 Proficiency Test

Table 2 summarizes the results obtained in the year 2021, for each variable (organic matter (%), assimilable P, K and Mg (mg/kg) and clay and sand granulometric fractions (%)), and for each sample (BIPEA and HUERTO) it shows the total number of analyses performed (N), taking into account that each laboratory provided up to three replicates, the number of data points used to obtain the consensus value, the consensus value and the standard deviation of the consensus value. For each parameter and sample, the number of results that were unsatisfactory (absolute value of Zscore greater than 3) or questionable (absolute value of Zscore between 2 and 3) and satisfactory (Zscore less than 2) were also recorded.

The percentage of satisfactory results was found to be higher in the HUERTO sample than in the BIPEA sample, mainly due to the higher satisfactory values in the determinations of organic matter, assimilable potassium and clay. It should be taken into account that for these three parameters the standard deviations

TABLE 2 | Results of the organic matter content (g/100 g), P, K and assimilable Mg mg/kg along with clay and sand granulometric fractions (g/100 g) for the BIPEA and HUERTO samples in the second exercise (2021): number of responses received (N), consensus value, standard deviation, number of values required to obtain the consensus value (n), number of satisfactory, questionable and unsatisfactory results.

	Organic matter (g/100 g)	Assimilable P (mg/kg)	Assimilable K (mg/kg)	Assimilable Mg (mg/kg)	Clay (g/100 g)	Sand (g/100 g)
BIPEA sample						
N	74	76	69	70	54	56
n	37	68	34	60	44	37
Consensus value	2.10	16.68	217.09	116.53	26.26	31.98
Standard deviation	0.12	3.63	8.82	25.49	3.70	2.04
No. of Satisfactory results	34	63	34	57	42	36
% of Satisfactory results	45.9%	82.9%	49.3%	81.4%	77.8%	64.3%
No. of Questionable results	5	5	1	5	2	2
No. of Unsatisfactory results	35	8	34	8	10	18
HUERTO sample						
N	74	76	69	70	56	56
n	58	67	51	65	50	39
Consensus value	0.69	14.81	272.38	181.82	24.89	37.77
Standard deviation	0.17	2.81	29.15	31.43	5.05	2.74
No. of Satisfactory results	55	63	49	63	47	38
% of Satisfactory results	74.3%	94.0%	71.0%	90.0%	83.9%	67.9%
No. of Questionable results	3	4	5	3	6	4
No. of Unsatisfactory results	16	9	15	4	3	14

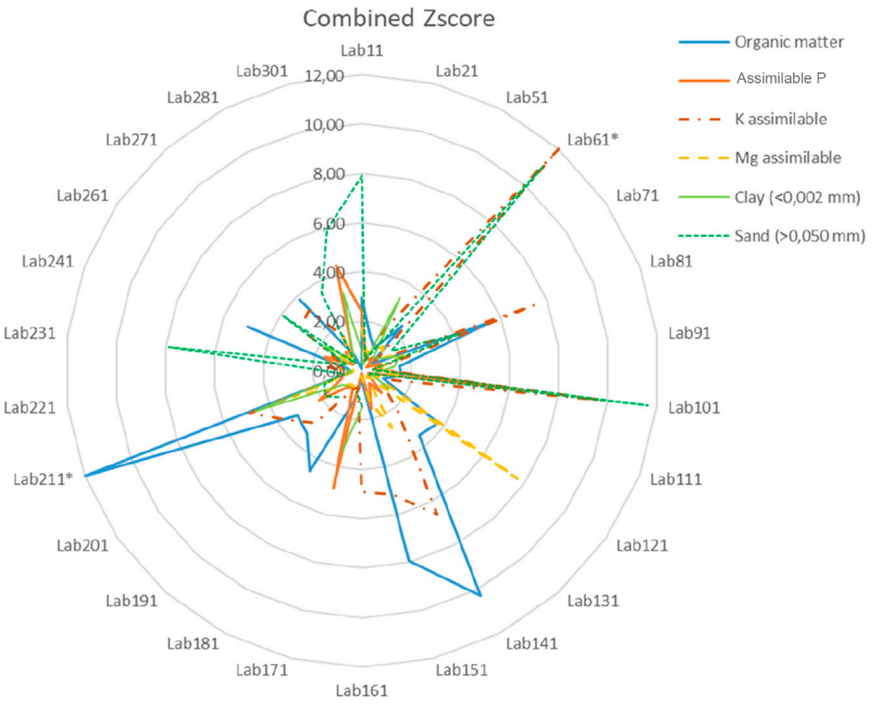

FIGURE 1 | Combined Zscore for each laboratory for all analyzed parameters (Organic Matter, Phosphorus, Potassium, Magnesium, Clay and Sand). * Values outside the range.

were higher for the HUERTO sample and this increased the range of acceptable values. In both samples there were a few questionable values, and, consequently, the unsatisfactory values were found to be higher for the BIPEA sample.

Full information on the Zscore values of each laboratory for each parameter is available in the **Supplementary Material**. A summary of the combined Zscore for each parameter is shown in **Figure 1**.

Table 3 shows the total number of laboratories participating in the exercise for each parameter, and the number of laboratories with satisfactory, questionable, or unsatisfactory ratings for each evaluated parameter after analyzing the combined Zscore for each laboratory.

TABLE 3 | Number of laboratories reporting responses for each parameter (organic matter, assimilable P, K and Mg, along with clay and sand particle size fractions) and number of laboratories falling into each classification (satisfactory, questionable or unsatisfactory) according to their combined Zscore for each parameter.

	Organic matter (g/100 g)	Assimilable P (mg/kg)	Assimilable K (mg/kg)	Assimilable Mg (mg/kg)	Clay (g/100 g)	Sand (g/100 g)
No. of laboratories responding	26	26	23	25	23	23
No. of Satisfactory results	13	21	13	22	19	14
No. of Questionable results	2	2	1	2	0	1
No. of Unsatisfactory results	11	3	9	1	4	8

In the WEPAL test (2024) 337 laboratories participated with soil samples and the range of unsatisfactory values was 10%, which is lower than the values in our exercise: 28% for the BIPEA sample and 15% for the HUERTO sample. It should be noted that the laboratories participating in the WEPAL exercise aimed to obtain a certification for their results, whereas our exercise had a different objective.

Organic Matter in the 2021 Proficiency Test

All laboratories provided a response on the organic matter content of the two samples. The organic matter content was higher in the BIPEA sample than in the HUERTO sample and the standard deviation was lower in the first case. This caused the range of acceptable values to be narrower in the BIPEA sample, resulting in many more unsatisfactory results.

The results of the 11 laboratories with an unsatisfactory combined Zscore for organic matter content are discussed in detail:

- Four laboratories (81, 151, 181, and 211) overestimated the organic matter content in all samples (6).
- One laboratory (191) overestimated some of the replicates of each sample (BIPEA and HUERTO).
- Five laboratories (121, 131, 201, 241, and 271) underestimated the organic matter content in the BIPEA sample only.
- One laboratory (141) underestimated the organic matter content in the BIPEA sample and overestimated it in the HUERTO sample, so it appears that there was a transcription error in the data and that the samples were mixed up.

Of the two laboratories with a questionable combined Zscore for organic matter content.

- One (61) underestimated the BIPEA sample.
- One (11) overestimated only one of the BIPEA sample replicates.

It should be noted that the majority of the laboratories measure oxidizable organic matter content using the Walkley and Black method. However, two laboratories (81 and 151) measured it by calcination, and another laboratory measured total organic matter using the DUMAS method (lab 211). The DUMAS procedure determines the total organic carbon released by calcination, so it is normal for it to overestimate (as do comparable calcination methods) the result of organic matter compared to the Walkley and Black method, which is based on the (non-total) oxidation of carbon. These methods were not separated because only three laboratories reported using them, which is insufficient for a separate analysis. Furthermore, the laboratories involved were aware that they overestimated the results for this particular measurement. In other intercomparison exercises, it was evident that comparing organic matter values obtained by different methods was difficult (for reference, the GLOSOLAN exercise should be considered). The Zscore values were excessively high in the present exercise.

The BIPEA exercise organizer analyzed organic carbon data separately depending on the method used. In the June 2024 test (personal communication, July 2024), 27 laboratories participated in the measurement of organic carbon by the oxidation method, and 67% achieved satisfactory results.

Assimilable Phosphorus in the 2021 Proficiency Test

All laboratories provided a response on the assimilable phosphorus content of the two samples. It should be noted that one of the conclusions of the 2019 exercise (Usón and Betrán, 2020) was a need to improve the results of assimilable phosphorus determination, and this was the reason why three replicates of each sample were requested.

The assimilable phosphorus content of the two samples did not differ greatly and the responses in terms of data dispersion were also similar. This was the parameter for which the highest number of satisfactory results were obtained for the two samples. When we reviewed the combined Zscore, it was also one of the parameters for which more laboratories obtained a satisfactory classification.

The results of the four laboratories with unsatisfactory or questionable combined Zscore for assimilable phosphorus content are discussed in detail:

- Two laboratories (171 and 301) had unsatisfactory overall results due to overestimation of assimilable phosphorus in the two samples. One laboratory (101) overestimated the assimilable phosphorus content only in the HUERTO sample, but the values were so high that the laboratory was classified as having unsatisfactory results overall.
- One laboratory (11) slightly underestimated the assimilable phosphorus in all samples.
- One laboratory (201) slightly overestimated the assimilable phosphorus in all samples.

The latter two laboratories obtained a questionable classification due to bias, to the extent that this prompted a detailed review of the protocol to try to correct it.

In the June 2024 BIPEA test (personal communication, July 2024) the range of acceptable values for assimilable phosphorus by the Olsen method was narrow (0.047–0.075 g/kg) with 77% of results being satisfactory. In our case the ranges of acceptable values were slightly higher as was the percentage of satisfactory results (84%).

Assimilable Potassium in the 2021 Proficiency Test

All but two of the laboratories provided a response on the assimilable potassium content of the two samples.

The HUERTO sample had a higher assimilable potassium content and a higher standard deviation, resulting in more values being classified as satisfactory. Nevertheless, in both samples the percentages of satisfactory values were lower than those obtained in the 2024 BIPEA test, which had a narrow range of acceptable values (0.17–0.20 g/kg) and obtained 77% acceptable values. The results of the 10 laboratories with an unsatisfactory combined Zscore for assimilable potassium content are discussed in detail as follows:

- Two laboratories (61 and 101) underestimated the assimilable potassium content in all samples.
- Three laboratories (81, 151, and 211) overestimated the assimilable potassium content in all samples.
- Four laboratories (191, 201, 261 and 271) underestimated the assimilable potassium content in the BIPEA sample only. Despite the international recognition of the BIPEA exercise, the determination of potassium in this sample again yielded results similar to those obtained in the assessment of organic matter. This sample showed greater heterogeneity in results, which can only be attributed to less homogeneity in the prepared soil.
- One laboratory (141) overestimated the assimilable potassium content in the BIPEA sample only.

The two laboratories with questionable combined Zscore for assimilable potassium content (131 and 191) underestimated the BIPEA sample.

Assimilable Magnesium in the 2021 Proficiency Test

All laboratories, except one, submitted a response regarding the assimilable magnesium content of the two samples.

The HUERTO sample had a higher assimilable magnesium content but the two samples had similar standard deviations, which made the ratings of the values similar in the two samples: many more satisfactory values than questionable or unsatisfactory. Both samples had a higher percentage of satisfactory values compared to those obtained in the BIPEA 2024 test (74%).

The results of the three laboratories with unsatisfactory or questionable combined Zscore for assimilable magnesium content are discussed in detail below:

- The only laboratory with an unsatisfactory result (121) overestimated the assimilable magnesium content of all samples.
- One laboratory with a questionable result (141) overestimated the assimilable magnesium content in one sample only.
- The other laboratory with questionable results (211) slightly overestimated the assimilable magnesium content in both samples.

Granulometric Fractions in the 2021 Proficiency Test

The soil particle size classes did not exactly match those of other exercises, so in this one we requested four textural classes: sand (2 mm<ø<0.05 mm), coarse silt (0.05<ø<0.02 mm), fine silt (0.02 mm<ø<0,002 mm), and clay (ø<0,002 mm) in the BIPEA exercise, five textural classes were requested; In addition, some laboratories did not send the silt fraction or they sent it unaggregated; therefore, we only analyzed the clay and sand fractions.

All but three of the laboratories submitted a response on the clay and sand content of the two samples.

Clay

The clay content was slightly higher in the BIPEA sample; however, the HUERTO sample had a higher standard deviation, leading to more unsatisfactory results in the BIPEA sample. In both samples the percentage of satisfactory results exceeded that of the 2024 BIPEA test (72%) although in this case the range of acceptable values was narrower (17.7–21.7 g/100 g) and had greater agronomic application.

The results of the four laboratories with an unsatisfactory combined Zscore for clay content are discussed in detail below:

- Two laboratories (171 and 211) underestimated the clay content in the two samples.
- One laboratory (51) overestimated the clay content in the two samples.
- One laboratory (301) overestimated the clay content in the BIPEA sample only.

Sand

The sand content was slightly higher in the HUERTO sample, and the standard deviations were small, causing a large number of unsatisfactory results in both samples. In both samples, the percentage of satisfactory results was lower than that of the BIPEA 2024 test (78%) although the range of acceptable values was similar (11.8–14.2 g/100 g).

The results of the eight laboratories with an unsatisfactory combined Zscore for sand content are discussed in detail below:

- Four laboratories (101, 231, 281, and 301) overestimated the sand content in the two samples.
- Two laboratories (81 and 261) underestimated the sand content in the two samples.
- One laboratory (11) overestimated the sand content in the BIPEA sample.
- One laboratory (61) underestimated the sand content in the BIPEA sample.

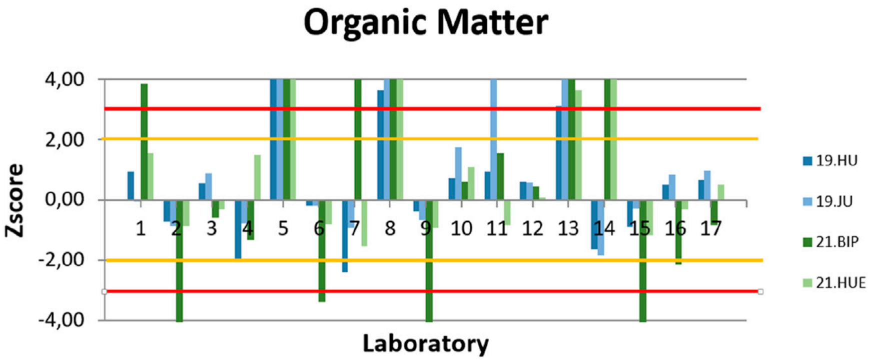

FIGURE 2 | Zscore for the results issued by each laboratories in the 2019 and 2021 proficiency tests for the organic matter parameter. In some cases, the Zscore value was found to be higher/lower than the plotted limit for laboratories 2, 5, 8, 10, 13, 14 and 15 for the 4 samples analyzed (HUERTO and JUNTAS in 2019 and BIPEA and HUERTO in 2021). The yellow line represents the lower limit of questionable results, and the red line represents the lower limit of unsatisfactory results.

The laboratory with a questionable rating (141) slightly overestimated the BIPEA sample and slightly underestimated the HUERTO sample.

Comparison of Results Between the 2019 and 2021 Proficiency Tests

Organic Matter

All of the laboratories that participated in the two tests (17) delivered organic matter results.

Figure 2 shows generally higher Zscore values in the second test, especially for the BIPEA sample. Six laboratories obtained satisfactory results in both samples of the two tests. Laboratories 5, 8, and 13 showed unsatisfactory values in the two exercises, and it is possible that these inconsistencies are due to the analytical method used, as other authors (Guerrero and Bertsch, 2020) have referenced these differences, and in other tests, such as WEPAL, the results were analyzed according to the method used. The case of laboratories 2, 14, and 15 was more relevant, as they went from satisfactory results in the 2019 test to unsatisfactory results in the 2021 test. The evolution has not been, in general terms, positive for this parameter.

Assimilable Phosphorus

In the comparison of Zscore values for phosphorus, all but one laboratory had acceptable average results in the 2021 exercise. Laboratory 11 significantly overestimated the phosphorus concentration (Zscore of 5.00 and 4.73 for each sample) as it did in one of the samples in the 2019 exercise. The rest of the laboratories either maintained or improved their rating in the results for this parameter (**Figure 3**). Globally, a trend toward improved results was observed, in agreement with (Becker et al., 2019) who also found that the repetition of proficiency tests contributed to the improvement of the results.

Assimilable Potassium

In this case, an apparent worsening of the score rating was evident, with 8 laboratories deemed to be unsatisfactory and 3 deemed to be questionable in 2019, to 13 rated unsatisfactory in 2021 (**Figure 4**). However, it should be noted that for one of the samples of the second test (BIPEA), the range of satisfactory values was very narrow and resulted in high Zscore values with relatively small differences accounting for 8 of the 13 unsatisfactory results.

Assimilable Magnesium

There was an apparent improvement in the rating of results for assimilable magnesium, going from 6 unsatisfactory and three questionable laboratories in 2019, to one unsatisfactory and two questionable laboratories in the 2021 test (**Figure 5**).

Granulometric Fractions

The interpretation of the Zscore values in the analysis of the grain size fractions was difficult in both tests. For clay content, the range of acceptable values was very wide in the two tests, leading the majority of laboratories to report acceptable values, with notable exceptions (**Figure 6**). It should be noted that the clay fraction is a much more important determinant of soil behavior and plant response than the other textural fractions (Porta et al., 2003), so values with very different responses were accepted as valid.

Conversely, the sand fraction showed a very narrow range of acceptable values, leading the majority of laboratories to report unsatisfactory results (**Figure 7**).

In addition, fewer results were received for the granulometric fractions in the second test. Specifically, in the case of the clay fraction (**Figure 6**) two laboratories did not send results for this parameter in 2021. For the sand fraction, there were also three laboratories that did not send results in the second test.

Overall Evolution of Laboratories

Figure 8 shows the combined Zs-core values (root mean square) of all laboratories for each proficiency test (1 and 2), which helps to interpret their comparison. The ratings went from 7 overall unsatisfactory and 4 questionable laboratories in 2019, to 5 unsatisfactory and 7 questionable in 2021. Although the results are not ideal, 10 of the 17 laboratories analyzed improved their overall Zscore, 3 maintained it, and only 4 clearly worsened it.

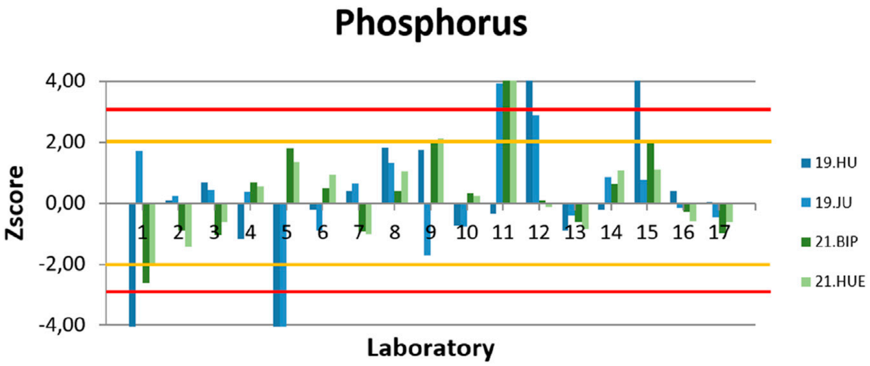

FIGURE 3 | Zscore for the results issued by each laboratories in the 2019 and 2021 proficiency tests for the phosphorus parameter. In some cases, the Zscore value was found to be higher/lower than the plotted limit for laboratories 5, 1, 12 and 15 for the 4 samples analyzed (HUERTO and JUNTAS in 2019 and BIPEA and HUERTO in 2021). The yellow line represents the lower limit of questionable results, and the red line represents the lower limit of unsatisfactory results.

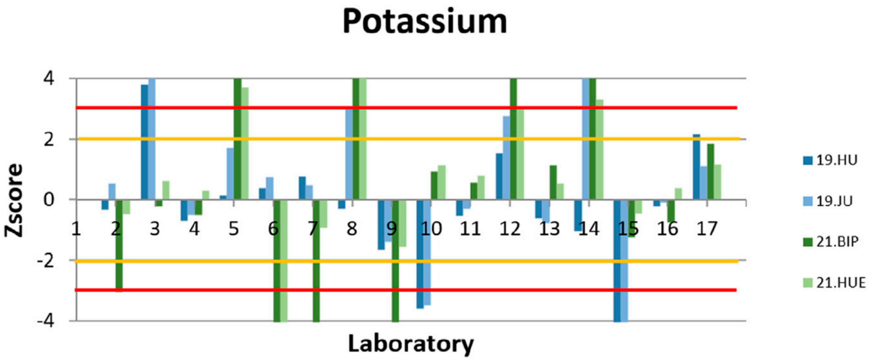

FIGURE 4 | Zscore for the results issued by each laboratories in the 2019 and 2021 proficiency tests for the potassium parameter. In some cases, the Zscore value was found to be higher/lower than the plotted limit for laboratories 5, 6, 7, 8, 8, 9, 12, 14 and 15 for the 4 samples analyzed (HUERTO and JUNTAS in 2019 and BIPEA and HUERTO in 2021). The yellow line represents the lower limit of questionable results, and the red one represents the lower limit of unsatisfactory results.

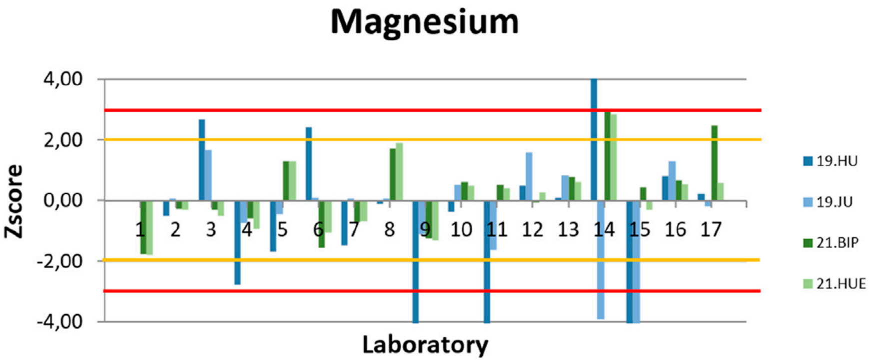

FIGURE 5 | Zscore for the results issued by each laboratories in the 2019 and 2021 proficiency tests for the magnesium parameter. In some cases the Zscore value was found to be higher/lower than the plotted limit for laboratories 9.11, 14 and 15 for the 4 samples analyzed (HUERTO and JUNTAS in 2019 and BIPEA and HUERTO in 2021). The yellow line represents the lower limit of questionable results, and the red line represents the lower limit of unsatisfactory results.

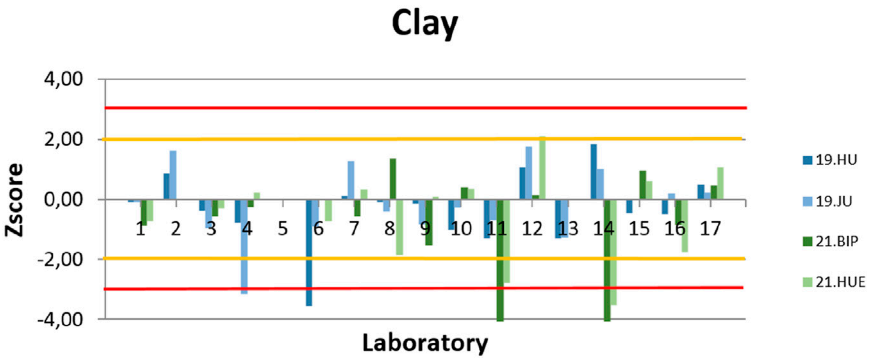

FIGURE 6 | Zscore for the results issued by each laboratories in the 2019 and 2021 proficiency tests for the clay parameter. In some cases, the Zscore value was found to be higher/lower than the plotted limit for laboratories 11 and 14 for the 4 samples analyzed (HUERTO and JUNTAS in 2019 and BIPEA and HUERTO in 2021). The yellow line represents the lower limit of questionable results, and the red one represents the lower limit of unsatisfactory results.

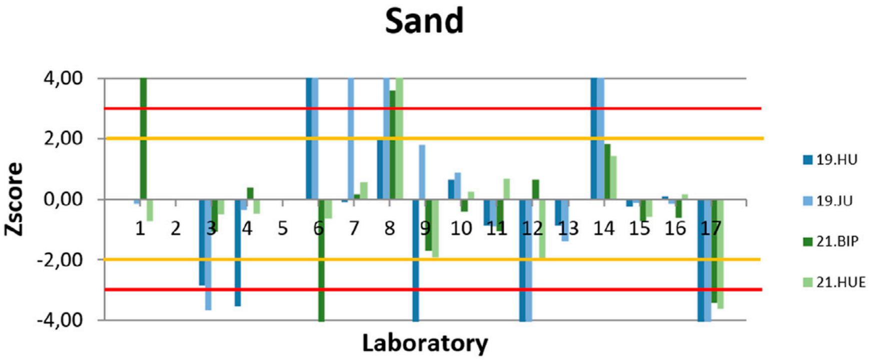

FIGURE 7 | Zscore for the results issued by each laboratories in the 2019 and 2021 proficiency tests for the sand parameter. In some cases, the Zscore value was found to be higher/lower than the plotted limit, for laboratories 1, 6, 7, 8, 9, 12, 14 and 17 for the 4 samples analyzed (HUERTO and JUNTAS in 2019 and BIPEA and HUERTO in 2021). The yellow line represents the lower limit of questionable results, and the red one represents the lower limit of unsatisfactory results.

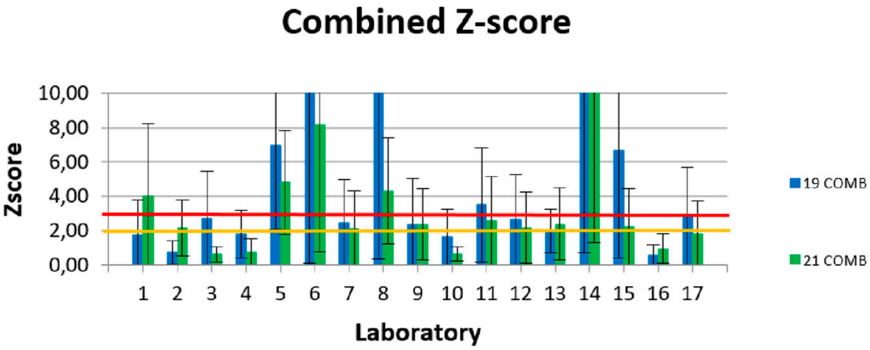

FIGURE 8 | Combined Zscore value for the 6 determinations performed (organic matter, phosphorus, assimilable potassium and magnesium and the textural fractions of clay and sand) for each laboratories in the 2019 and 2021 proficiency tests. The attached line at the top represents the variability of the Zscore obtained by each laboratory in each edition of the tests. The yellow line represents the lower limit of questionable results, and the red one represents the lower limit of unsatisfactory results.

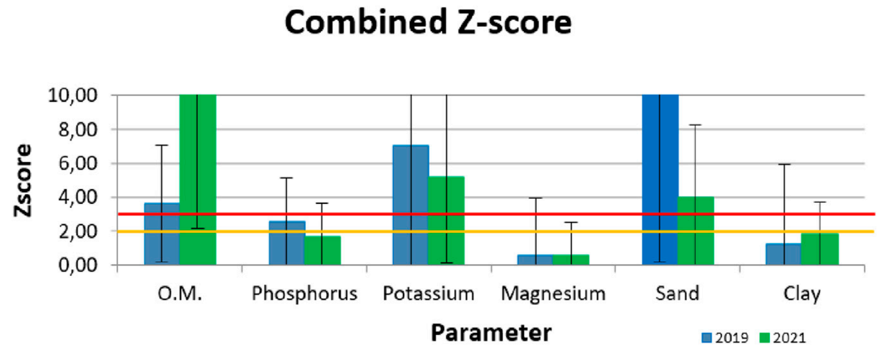

FIGURE 9 | Combined Zscore value for the 17 laboratories for the 6 determinations performed (organic matter, phosphorus, assimilable potassium and magnesium and the textural fractions of clay and sand) in the 2019 and 2021 proficiency tests. The attached line at the top represents the variability of the Zscore obtained from each laboratories in each edition of the tests. The yellow line represents the lower limit of questionable results, and the red one represents the lower limit of unsatisfactory results.

In the analysis of variance performed individually for each laboratory, there were statistically significant differences ($P < 0.05$) observed for only two laboratories: laboratories 3 and 4; in both cases, the combined Zscore was lower in the 2021 test compared to the 2019 test.

Overall Evolution of the Analyzed Parameters

Regarding the evolution of the scores for each parameter, the situation was also observed to be uneven when analyzing the set of results obtained (combined Zscore) (**Figure 9**). Several studies observed that the repetition of these proficiency tests improves results (Becker et al., 2019; Houba et al., 1996) and that they are therefore a good tool for improving the quality of analytical laboratories.

The combined Zscore value in the two tests remained satisfactory for clay and assimilable phosphorus content, which is a considerable achievement, since other studies have reported difficulties in homogenizing results for this parameter (Hanson et al., 1998).

In the two tests, the Zscore values remained unsatisfactory for assimilable potassium content, and sand content went from unsatisfactory results in the 2019 test to questionable results in the 2021 test. It should be noted that the second test used an average of 6 values (instead of 2 in the first exercise) and that the ranges of satisfactory values have decreased.

For the organic matter content, the results were found to be the opposite, going from questionable values in the 2019 test to unsatisfactory in the 2021 test. It should be taken into account that evaluating the organic matter content in Spanish soils is one of the objectives of the environmental monitoring program of the CAP Strategic Plan (MAPAMA, 2023) so the results obtained in this work are relevant for analyzing the 128,000 samples collected for this purpose.

Finally, the estimation of the assimilable magnesium content went from questionable mean values in the 2019 test to satisfactory values in the 2021 test. When performing the ANOVA, this was the only parameter showing significant differences with a $P < 0.10$ ($P = 0.088$). Therefore, it can be stated that the assimilable magnesium determination significantly decreased its Zscore value in the second proficiency test compared to the first one performed.

CONCLUSIONS

We analyzed the combined Zscore obtained by each participating laboratory on the results of six essential soil fertility parameters. In the 2021 exercise, only five of the 17 laboratories obtained a satisfactory rating, seven received a questionable rating, and another five were found to be unsatisfactory. In 2019, these figures were 6, 4, and 7, respectively. Between 2019 and 2021, 4 laboratories improved their Zscore rating, 4 worsened, and 9 remained the same; of these, 4 remained unsatisfactory and 2 remained questionable.

The variability found among laboratories makes the results obtained a matter of chance, and the interpretation or application of these results can lead to radically wrong decisions. This is unacceptable in the national and European contexts of interest in soil and its conservation.

Analyzing the combined Zscore for the parameters revealed that all laboratories maintained their rating except for the assimilable phosphorus result, which indicated an improvement from questionable in 2019 to satisfactory in 2021. The results for organic matter, assimilable potassium, and sand remained unsatisfactory, while those for magnesium and clay remained satisfactory.

In the second test (2021), the collection of replicates did not provide much information but substantially complicated the management of the exercise. The results obtained showed the need to periodically carry out this type of proficiency test.

Finally, the two intercomparison exercises studied in this paper demonstrated the urgent need to standardize results between laboratories offering soil fertility analysis in Spain. This has been communicated to the Ministry of Agriculture, Fisheries and Food, and the main proposal for the future is the designation of a national reference laboratory in this field. This was already achieved with the designation of the Agro-Environmental Laboratory as the national reference laboratory on 1 October 2024.

Within this framework, the following additional measures are proposed:

- Annual intercomparison exercise. The two-sample format has proven to be convenient and efficient. It should include at least, the usual parameters.
- Sharing of analysis methods, with a view to standardizing their application. This applies at least to those methods that are considered official in Spain that have become obsolete, not so much in terms of extraction techniques as in terms of determination techniques. In practice, this would involve reviving the Official Commission on Analysis Methods, which ceased operations in the early 1990s.
- Attempt to carry out a comparative study of methods. To accomplish this, more information must be required when sending results, and more laboratories with different methods must participate, with some even participating with more than one method.
- Encouraging participation in parameters offered by fewer laboratories, such as saturated paste, microelements, heavy metals, water retention; considering including parameters that are not strictly considered soil fertility parameters or that are rare in the market, such as phytosanitary residues, biological parameters, aflatoxins, etc.

All information obtained should be used to inform the design of future exercises.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/**Supplementary Material**, further inquiries can be directed to the corresponding author.

AUTHOR CONTRIBUTIONS

AU funding acquisition to conduct the study, conceived and designed research, collected data, statistical analyses and wrote the manuscript. JB also participated in the design of the research, collected data, performed the figures and tables and wrote the manuscript. MS participated in revising the manuscript and references. All authors contributed to the article and approved the submitted version.

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CONFLICT OF INTEREST

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

GENERATIVE AI STATEMENT

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontierspartnerships.org/articles/10.3389/sjss.2025.14838/full#supplementary-material

REFERENCES

Becker, R., Sauer, A., and Bremser, W. (2019). Fifteen Years of Proficiency Testing of Total Petrol Hydrocarbon Determination in Soil: A Story of Success. *Accreditation Qual. Assur.* 24, 289–296. doi:10.1007/S00769-019-01383-X

Bierer, A. M., Leytem, A. B., Rogers, C. W., and Dungan, R. S. (2021). Evaluation of a Microplate Spectrophotometer for Soil Organic Carbon Determination in south-central Idaho. *Soil Sci. Soc. Am. J.* 85, 438–451. doi:10.1002/SAJ2.20165

BOE (1975). *BOE-A-1976-6778 Orden De 5 De Diciembre De 1975 Por La Que Se Aprueban Como Oficiales Los Métodos De Análisis De Suelos Y Aguas*, 6458–6491.

BOE (2024). *BOE-A-2024-19791 Orden APA/1044/2024, De 23 De Septiembre, Por La Que Se Designa Laboratorio Nacional De Referencia En Materia De Análisis De Fertilidad De Suelos Agrarios*, 120669–120670.

Buczko, U., Totubaeva, N., and Kuchenbuch, R. O. (2024). Comparison of the Machigin and CAL Methods for Extraction of Plant Available P in Soils. *Commun. Soil Sci. Plant Anal.* 55, 2217–2231. doi:10.1080/00103624.2024.2345149

Guerrero, A., and Bertsch, F. (2020). *Primer Informe Del Ejercicio De Intercomparación De La Red Latinoamericana De Laboratorios De Suelos-LATSOLAN*. Roma. doi:10.4060/ca9251es

Hanson, D., Kotuby-Amacher, J., and Miller, R. O. (1998). Soil Analysis: Western States Proficiency Testing Program for 1996. *Fresenius J. Anal. Chem.* 360, 348–350. doi:10.1007/s002160050707

Houba, V. J. G., Uittenbogaard, J., and Pellen, P. (1996). Wageningen Evaluating Programmes for Analytical Laboratories (WEPAL), Organization and Purpose. *Commun. Soil Sci. Plant Anal.* 27, 421–431. doi:10.1080/00103629609369565

Kweon, G., Lund, E. D., Maxton, C., Lee, W. S., and Mengel, D. B. (2015). Comparison of Soil Phosphorus Measurements. *Trans. ASABE* 58, 405–414. doi:10.13031/trans.58.10903

Laso Sánchez, J. M., and García-Patrón Peris, A. (2009a). *Evaluación De Resultados De Ensayos De Aptitud*. Madrid: V Iberlab. 1–5.

Laso Sánchez, J. M., and García-Patrón Peris, A. (2009b). *Tratamientos Estadísticos De Aptitud: Aplicación De La Mediana Para Detección De Resultados Anómalos*. Madrid: V Iberlab. 6–11.

MAPAMA. (2023). Programa De Vigilancia Ambiental Del Plan Estratégico De La Pac Para España 2023-2027: Planteamiento General Y Primer Avance De Indicadores De Contexto/Estado Medioambientales Y Climáticos.

Martínez Antonio, M. E. (2021). *Del Laboratorio Agrario Regional Del Ebro Al Laboratorio Agroambiental. 50 Años De Historia*, 1971–2021.

Ministerio de Agricultura (1994). "Métodos Oficiales De Análisis," in *Tomo III*, 662.

Porta, J., López-Acevedo, M., and Roquero, C. (2003). "Edafologia Para La Agricultura Y El Medio Ambiente, 3ª," in *Edafología: Para La Agricultura Y El Medio Ambiente*. Madrid: Mundi-Prensa.

SECS. (2018). Inventario Laboratorios De Suelos. Available online at: https://www.secs.com.es/inventario-%20laboratorios-de-suelos/ (Accessed April 27, 2025).

Usón, A., and Betrán, J. (2020). Puesta a Punto De La Metodología De Ejercicios De Intercomparación Para Análisis De Fertilidad De Suelos. Primeros Resultados. *Span. J. Soil Sci.* 10, 191–197. doi:10.3232/SJSS.2020.V10.N3.01

WEPAL (2024). "International Soil-Analytical Exchange," in *Final Annual Report 2023*, 372.

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Integrated Vascular Analysis System of Olive Cultivation: Savia Olivar Project

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Olive trees are widely cultivated crops, especially in Mediterranean countries, which requires new practices to maintain productivity, optimize resource use and improve the quality of the environment. Integrated production seeks to achieve these objectives, but this requires rapid and effective methods to plan crop nutrition. Sap extracted using a modified Scholander chamber could provide an accurate method for determining the nutritional status of olive trees. To verify this, two trials were conducted in integrated production systems in southern Spain over two periods of time (2018–1019 and 2022–2024). The trials were carried out in five farms in the provinces of Jaén, Granada and Seville, comparing the nutrient concentrations in sap, leaves and soil from Picual and Hojiblanca olive trees. In the first period (2018–2019), critical times when nutrient flux in the sap increased were identified as spring, early fall, winter, and the first half of July. These periods were selected for sampling in the second period (2022–2024). Sap, leaves and soil were analyzed, determining macro- and micronutrients, pH and electrical conductivity. In the first trial, monthly sampling was successful, although in autumn 2022, a very dry year, little sap was extracted. From April 2023 onwards, the amount of sap recovered, which demonstrated the sensitivity of sap extraction to climatic variations and the phenological state of the olive tree. Soil analyses showed pH from 7.9 to 8.5 and electrical conductivity from 1.1 to 5.9 dS m^{-1}. Nutrient concentrations in leaf were higher than in soil and in soil higher or equal than in sap, except for K, the most abundant element in sap, with concentrations exceeding those in soil. Concentrations of Fe, Cu, Mn and Zn increased in 2022 compared to 2018, possibly due to climatic differences. Sap analysis can complement leaf and soil analyses for a more balanced fertilisation in olive orchards.

Keywords: olive crop, integrated production, macro- and micronutrients, nutritional status, soil, sap, leaves

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INTRODUCTION

Olive tree (*Olea europaea* subsp. *Europaea var. Europaea L.*) is likely the oldest cultivated tree in approximately seventy-seven countries worldwide (El Yamani and Cordovilla, 2024), covering an area of over 11 million hectares (IOC. International Olive Council, 2022). In Europe, it spans the entire Mediterranean region where it originated and remains the dominant cultivated tree (IOC. International Olive Council, 2003).

These vast cultivation areas and conventional agricultural practices have led to intense soil degradation processes (Porta et al., 1999), particularly due to water erosion (Lima et al., 2023), excessive tillage (Aguilera-Huertas et al., 2022), and overuse of chemical fertilizers (Sutton et al., 2013). These processes produce significant losses of organic carbon, nitrogen (Abid and Lal, 2008), soil biodiversity (Morgado et al., 2020; Morgado et al., 2022), fertility (Porta et al., 2008; Domouso et al., 2024), and degradation of soil properties (García-Orenes et al., 2012). Some authors agree that the use of vegetative covers improves soil health (Espejo-Pérez et al., 2013; Sastre et al., 2017).

Integrated production is an agricultural system for food production that optimizes resources and natural production mechanisms to ensure long-term sustainable agriculture. The goal is to use cultivation techniques compatible with social needs, environmental protection, and agricultural production (BOJA, 2008). The Integrated Olive Production Regulation in Andalusia (Junta de Andalucía, 2016) outlines a set of agronomic practices classified into various areas, including fertilization and soil management. In the fertilization section, it is stated that mineral fertilization should take into account crop extractions, soil fertility levels, plant nutritional status, and contributions from other sources (water, organic matter, etc.). To meet these objectives, foliar analyses are required in the first half of July.

Leaf nutrient analysis, which is used to determine the status and fertilization needs of plants, has been widely accepted as a good method for diagnosing deficiencies such as nitrogen (Fernández-Escobar et al., 2011). However, this method is not effective for detecting excess nutrients caused by over-fertilization (Weinbaum et al., 1992). Moreover, changes in crop management can affect nutrient dynamics and reference values. Therefore, integrated production requires periodic reviews of the analyses methods and reference values.

Sap is considered a precise medium for determining plant nutrients (Esteves et al., 2021). However, its use has not been widely adopted because of limitations in the extraction and measurement methods (Esteves et al., 2021). In recent years, various studies (Carella et al., 2016) have helped establish nutrient levels in the xylems of different plants, identifying dynamics related to nutrient supply, plant water status, and soil type. Some authors (Do Amarante et al., 2006) studied nitrogen and amino acid content in the xylem of various legumes under controlled conditions; Cabañero and Carvajal (2007) studied K, Mg, and Ca levels in xylem samples from *Capsicum annuum L.* using atomic absorption spectroscopy. More recently, Larbi et al. (2010) used xylem samples to study Fe levels in *B. vulgaris L.* plants. Guérin et al. (2007) used xylem samples from *L. ovalifolium Hassk* collected in spring to study nutrient mobility and the interaction of N and C compounds in plants with and without fertilization. In olives, xylem morphology is associated with plant–water availability (Bacelar et al., 2007; Rousseaux et al., 2009).

The aim of this study was to assess the effectiveness of sap extraction using a modified Scholander-Hammel chamber for quickly determining the nutritional status of olive trees depending on soil management, as a complementary method to foliar and soil analyses. To achieve this goal, we compared the nutrient concentrations in sap, leaves, and soil from Picual and Hojiblanca olive trees, which are cultivated under integrated production in different provinces of southern Spain, over several years.

MATERIALS AND METHODS

Study Area

This study was conducted over two periods of time (2018–2019 and 2022–2024) on five integrated production farms located in the provinces of Jaén, Sevilla, and Granada (southern Spain). All farms were under integrated production (Junta de Andalucía, 2016), and the trees were not deficient, as confirmed by leaf analysis data collected in the first half of July before the start of the experiment. All farms were irrigated locally (between 1,500 and 2,200 m^3 ha^{-1}), and soil management practices included vegetative cover between the rows of olive trees. The agronomic characteristics of the study farms are detailed in **Table 1**.

Fertilization practices were very similar across most farms, including soil application, foliar application, and fertigation. Soil was fertilized in February or March by applying nitrogen (either nitrate or ammoniacal) and potassium sulfate. Occasionally, commercial fertilizers containing N, P, K, S, and B were added. Foliar fertilization was usually carried out three times per year: in March, May/June, and December, with N (urea, ammonium sulphate), K (potassium nitrate, potassium chloride), P, and B (monoammonium phosphate, sodium borate).

Fertigation occurred weekly from June to October. Under optimal conditions, when water availability was allowed, the annual water contribution was approximately 1,300 m^3 ha^{-1}. In the irrigation water, ammonium nitrate, potassium chloride, and phosphoric acid were added.

Climatic Characteristics

The climatic data were taken from the agroclimatic stations belonging to the Agroclimatic Information Network of Andalusia (RIA, 2024), selecting those closest to the farms under study. As seen in **Figure 1**, precipitation was higher during 2018 and 2019, with greater amounts in Dílar, Fuensanta, and Osuna than in Luenga/Guadiana, where the differences between periods were smaller. During the second study period (2022–2024), especially in 2022, precipitation was considerably lower.

Experimental Design

In each farm, four plots were established, each consisting of six trees arranged in two consecutive rows. The plots were separated by an intermediate row of olive trees to ensure their independence. All sample types were collected monthly from 2018 to 2019 and quarterly from 2022, 2023, and 2024. To standardize the data treatment, samples were grouped into three-month sets.

Sample Collection and Analyses

Four composite soil samples were collected from each plot of each farm in the area where irrigation was applied for subsequent

TABLE 1 | Agronomic characteristics of the study farms.

Farm	Dílar	Fuensanta	Cortijo Guadiana	Cañada Luenga	Osuna
Location	Granada	Granada	Jaén	Jaén	Sevilla
Olive trees	Picual	Hojiblanca	Picual	Picual	Hojiblanca
Age (years)	25	23	24	24	16
Plantation framework (m)	8 × 4	9 × 9	7 × 7	7 × 7	6 × 7
Fertilization	Cover + Fertigation-cation + Leaf fertilization	Cover + Fertigation-cation + Leaf fertilization	Fertigation-cation + Leaf fertilization	Fertigation-cation + Leaf fertilization	Fertigation-cation + Leaf fertilization
Soil classification (IUSS Working Group WRB, 2022)	Calcaric Cambisols	Haplic Calcisols	Calcaric Regosols	Calcaric Regosols	Calcaric Luvisols

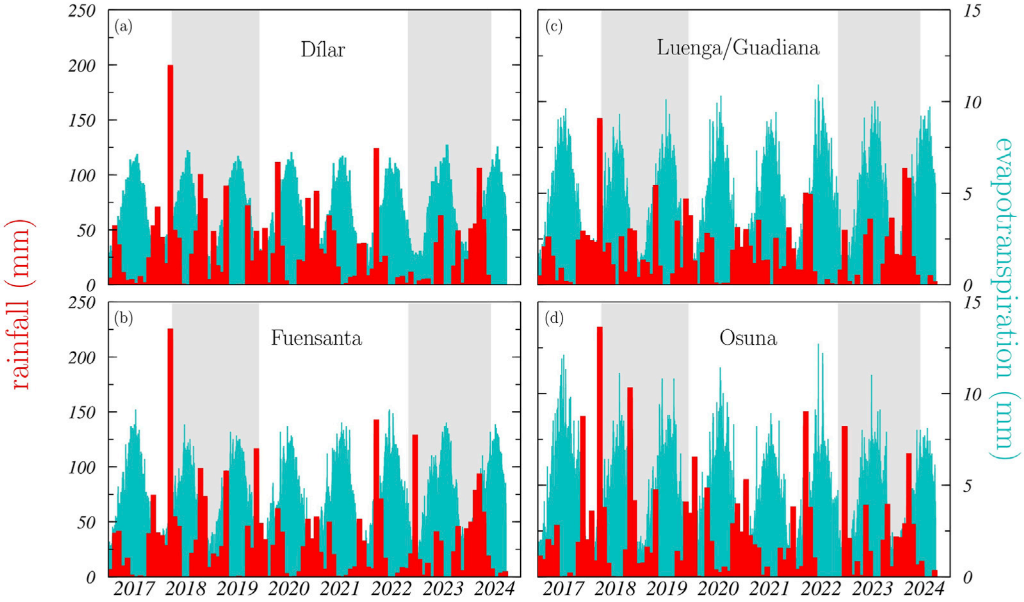

FIGURE 1 | Precipitation and potential evapotranspiration at the four study sites, according to the data extracted from RIA (2024). Shaded areas indicate the sampling periods. Blue lines represent potential evapotranspiration, while red lines indicate precipitation. **(a)** Dílar farm; **(b)** Fuensanta farm; **(c)** Luenga/Guadiana farm; **(d)** Osuna farm.

laboratory analyses. Leaf samples were collected following the guidelines provided by Fernández-Escobar et al. (1999). On each sampling date, 20 leaves were collected from around the crown of each olive tree in the plot. Leaves corresponding to the previous year's growth were collected. The branches used for sap extraction were harvested between 08h00 and 10h00, depending on the time of year and always after sunrise. The branches were placed in dark bags and quickly transported, along with the leaves, to the Olivarum laboratory, which is part of the Fundación Caja Rural de Jaén at the Geolit Technological Park in Mengíbar (Jaén).

Soil Analysis

The soil samples were initially analyzed at the Department of Soil and Agricultural Chemistry of the University of Granada. During the study, the following analyses were conducted on samples collected from the wet bulb of each tree: pH 1:2.5, soil/water suspension, and electrical conductivity (EC) in soil-saturation extract (U.S. Salinity Laboratory Staff, 1954) were measured using a Crison Basic 20 pH meter and a Crison Basic 30 conductivity meter, respectively; oxidizable carbon was determined using Tyurin's method (Tyurin, 1951); total nitrogen was measured using a LECO C/N analyzer; assimilable phosphorus was analyzed using the Watanabe and Olsen method (Watanabe and Olsen, 1965); exchangeable cations and cation exchange capacity were determined following the Soil Conservation Service Method (1972); soluble K, Ca, Na, and Mg (water-soluble elements in saturation extract) and Cu, Mn, and Zn were extracted using DTPA (Quevauviller et al., 1998).

Leaf Analysis

Leaf samples were analyzed at Olivarum. After washing with Triton 0.1% and distilled water, the leaves were incinerated in a muffle furnace for a minimum of ten hours (Ministerio de Agricultura, Pesca y Alimentación, 1994). They were then

TABLE 2 | Constituents and soil properties in the study farms. Different letters represent the statistical differences between farms (Tukey $p \leq 0.05$). Mean value and standard desviation are presented in the table.

Soil's properties	Farms				
	Dílar	Fuensanta	Luenga	Guadiana	Osuna
Sand (%)	55.9 ± 5.1d	28.7 ± 5.1b	15.2 ± 1.0a	11.8 ± 1.5a	40.1 ± 2.0c
Coarse silt (%)	11.1 ± 2.8b	13.3 ± 0.6b	13.8 ± 2.0b	10.1 ± 1.3b	4.0 ± 2.1a
Fine silt (%)	17.8 ± 3.4b	27.3 ± 1.5c	33.9 ± 1.3c	30.3 ± 5.9c	10.1 ± 1.5a
Clay (%)	15.1 ± 1.2a	30.7 ± 1.9b	37.1 ± 2.0b	47.8 ± 6.7c	45.7 ± 0.9c
Texture classification	sandy loam	loamy	clayey	clayey	clayey
pH	7.7 ± 0.5	7.7 ± 0.2	7.9 ± 0.5	8.0 ± 0.4	7.6 ± 0.6
EC (dS m^{-1})	2.1 ± 0.1	1.3 ± 0.6	1.7 ± 0.3	1.7 ± 0.7	1.5 ± 0.5
CEC (cmol$_c$ kg^{-1})	10.9 ± 1.2a	13.0 ± 1.7b	12.7 ± 0.5ab	16.7 ± 2.5c	23.4 ± 0.6d
Na (cmol$_c$ kg^{-1})	0.7 ± 0.2a	0.8 ± 0.3a	1.2 ± 0.3b	1.2 ± 0.3b	0.9 ± 0.3ab
Mg (cmol$_c$ kg^{-1})	8.6 ± 5.4ab	6.1 ± 1.5a	7.6 ± 3.7ab	10.9 ± 4.8c	5.0 ± 1.7a
CaCO$_3$ (%)	13.5 ± 1.1a	40.7 ± 3.8b	58.9 ± 6.0c	63.2 ± 4.4c	13.3 ± 1.2a
Available H$_2$O (%)	13.7 ± 2.7	13.3 ± 0.5	12.3 ± 0.3	13.6 ± 1.4	10.8 ± 0.7
OC (%)	2.9 ± 0.4b	1.9 ± 0.4a	2.7 ± 0.5b	2.8 ± 0.2b	2.7 ± 0.9b
N (%)	0.18 ± 0.03	0.17 ± 0.10	0.20 ± 0.07	0.17 ± 0.02	0.18 ± 0.05
P$_2$O$_5$ (ppm)	64.1 ± 12.1b	73.0 ± 9.4bc	80.5 ± 5.9c	84.1 ± 12.8c	36.0 ± 8.7a
K (cmol$_c$ kg^{-1})	0.6 ± 0.3a	1.1 ± 0.2b	0.6 ± 0.2a	0.8 ± 0.3ab	1.1 ± 0.4b
Mn (ppm)	16.2 ± 5.0	24.1 ± 4.7	13.7 ± 1.4	18.8 ± 5.5	32.7 ± 5.2
Cu (ppm)	22.3 ± 4.9	10.3 ± 2.1	20.3 ± 2.7	26.0 ± 5.8	26.8 ± 4.1
Zn (ppm)	0.9 ± 0.4	0.5 ± 0.1	11.9 ± 1.8	17.8 ± 3.9	1.1 ± 0.8

dissolved in hydrochloric acid, and the concentrations of P, K, Ca, Mg, Mn, Cu, and Zn were measured by optical ICP (Inductively Coupled Plasma Optical Emission Spectrometry).

Sap Analysis

Sap extraction was performed at Olivarum using a modified Scholander-Hammel chamber with an extension that allowed the use of entire branches. Once introduced, the protruding ends of the branches were cleaned with distilled water to prevent possible contamination and were cut, leaving approximately 5 cm with respect to the chamber, to facilitate the exit of the sap. The applied pressure never exceeded 40 bar, and sap expulsion began when the pressure reached 20 bar. The sap was kept as far from light as possible because it is photosensitive. Sap samples were frozen at −24°C until further analyses. Electrical conductivity and pH were measured using glass electrodes, and macro- and micronutrients were measured using optical ICP.

Statistical Analysis

For the statistical analysis of the samples, IBM SPSS Statistics 19 software (IBM Corp, 2010) and R were used (R Development Core Team, 2017). Normality and homocedasticity were checked prior to all the analyses using the Kolmogorov–Smirnov test and Levene's test, respectively. For cases not meeting the normality or homogeneity requirements, the data were transformed to assume statistical parametric assumptions. ANOVA was performed to establish the differences between the different soil constituents measured on the farms studied. In order to study the differences between the farms studied, a Tukey´s test ($p < 0.05$) was subsequently applied.

For the figures presented, uncertainties include both those type B associated to the measurement procedure and those type A linked to the sample variability. Both were added quadratically. Uncertainty bars correspond to a coverage factor $k = 1$.

As **Supplementary Material**, we have added Pearson's bivariate correlations between the 3 matrices studied: soil to leaf, soil to sap and sap to leaf.

RESULTS

Initial Soil Characterization

The most important soil constituents and properties are summarized in **Table 2**. Soil texture varied among the farms. pH was basic in all cases, but it was higher in Luenga and Guadiana, which also had the highest calcium carbonate content, exceeding 50%. All farms had plant cover due to integrated production, which helped to maintain relatively high organic carbon levels. Similarly, N, P, and K contents were maintained within typical ranges, as regular soil analyses guided fertilization practices.

Notably, Osuna had a significantly lower phosphorous content compared to Dílar, which had the next lowest levels. The difference between farms was particularly evident in the phosphorus values, which were nearly 50% lower at Osuna compared to Dílar, and also lower than those in Luenga and Guadiana, where the highest values were found. These three farms (Osuna, Luenga, and Guadiana) showed the greatest variation between sampling periods.

The soil was deep with no signs of excessive erosion due to gentle slopes, no plowing, and the maintenance of shredded pruning residues along with vegetation cover between rows.

The First Study Period (2018–2019)

Leaf Analysis

Results from the first study period (2018–2019) are presented in **Figure 2**. Data were grouped by trimester, with the first data point representing the average of the five farms during April-June 2018, followed by three additional points for the remaining 2018 and

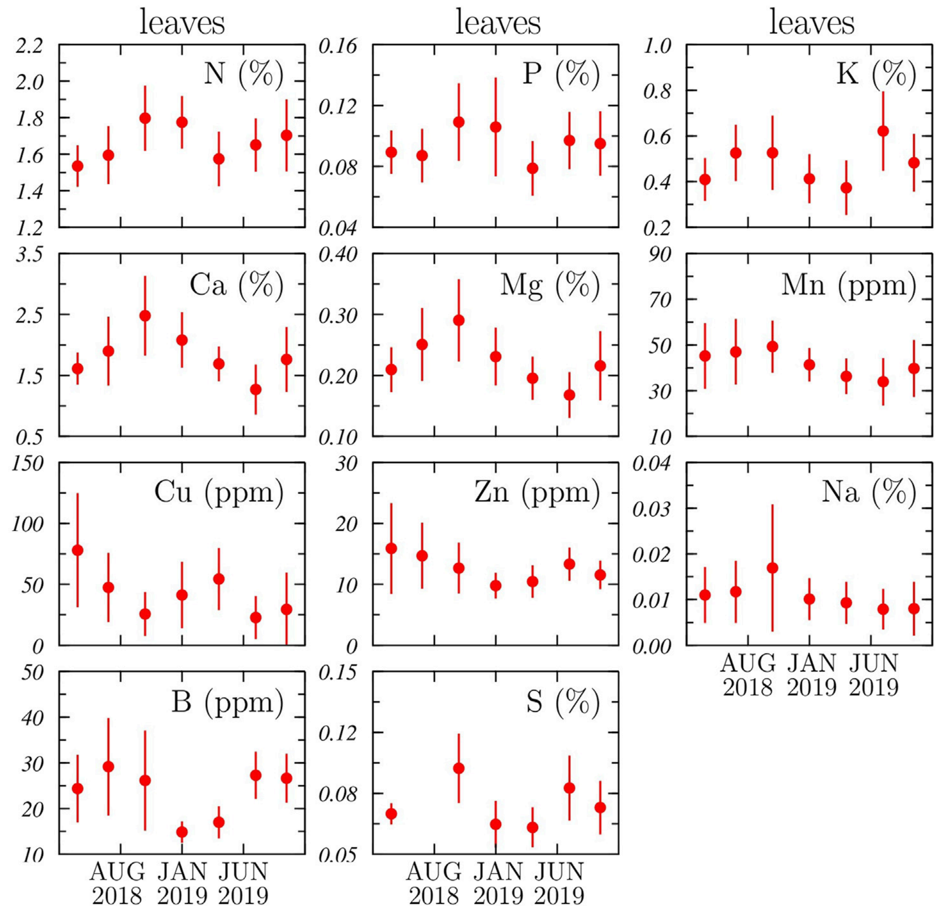

FIGURE 2 | Concentrations of nutrients in leaves for the first study period (2018–2019). Uncertainties include both those type B associated to the measurement procedure and those type A linked to the sample variability. Both were added quadratically. Uncertains bars correspond to a coverage factor k = 1.

2019 periods. The dynamics of N, P, and K in leaves were similar to each other, showing the lowest concentrations in the first trimester (April-June 2018) and the highest in October-December 2018 and January-March 2019.

N and P concentrations were significantly higher during the October-December 2018 and January-March 2019 periods, whereas K showed the opposite pattern, peaking during the last two trimesters of 2019. Ca and Mg exhibited similar dynamics, with the lowest concentrations occurring in the first and second trimesters of both years and the highest in the same period as the N, P, and K peaks (October-December 2018).

Mn and Zn concentrations were higher in 2018 than in 2019, but neither micronutrient showed signs of deficiency (Mn > 40 ppm and Zn between 10 and 20 ppm) (Fernández-Escobar et al., 1999; Nieto et al., 2017). An inverse relationship was noted between K and the concentrations of Ca, Mg, and Mn in leaves.

The Cu levels in leaves were highest in spring and fall, reflecting their use in phytosanitary treatments, and were significantly above the 4 ppm threshold considered typical for July. B levels ranged from 10 to 30 ppm, increasing during foliar applications, especially in July, August, and September, where some farms had concentrations exceeding 40 ppm.

S concentrations in leaves were higher in the October-December period, but there was considerable variability among farms.

Sap Analysis

Results from sap analysis are shown in **Figure 3**. As with leaf analysis, differences between farms were minimal, but significant variations were observed across sampling periods. The pH of sap was generally stable, showing slight increases from July 2018 to early 2019, with a notable decrease in September 2019, possibly due to fertilizer applications.

K concentrations in sap were lower in the last trimester of both years, ranging from 20 to 30 ppm, whereas the highest concentrations (around 60 ppm) were associated with spring fertilization. Nitrate and P levels showed similar patterns in 2018, with P being more stable but with higher standard deviations. Both elements increased during the first two trimesters of 2019, then slightly decreased at the end of 2019.

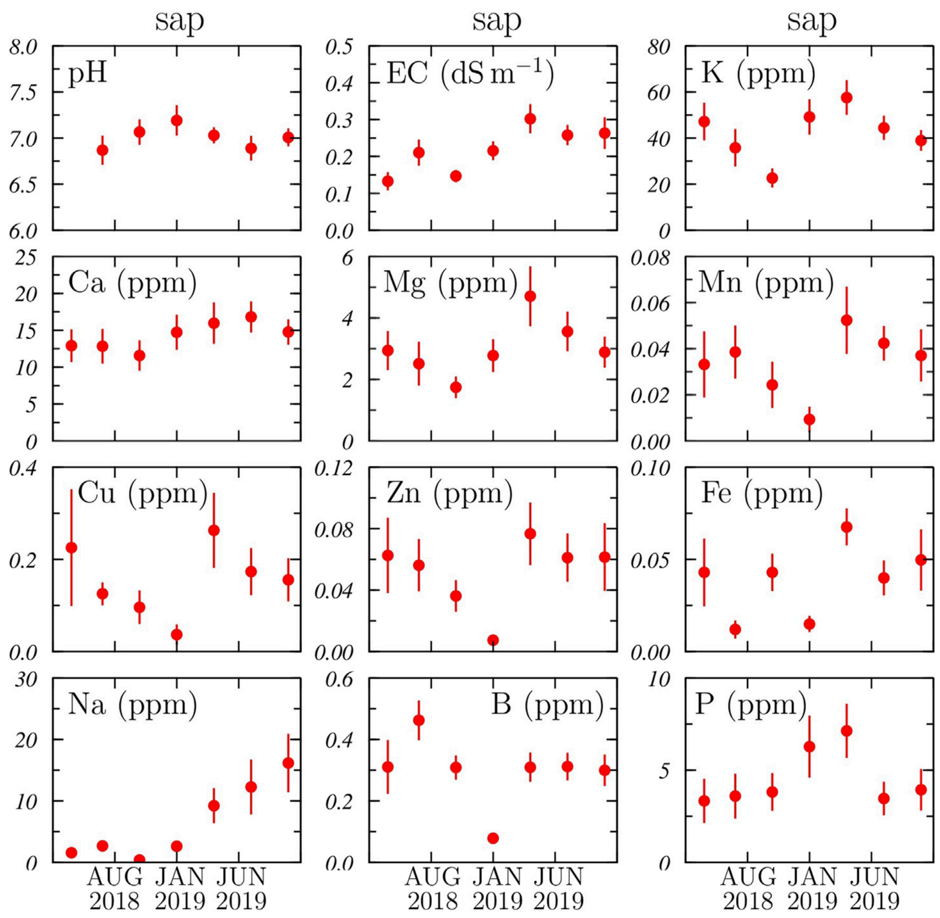

FIGURE 3 | Values of pH, EC and different nutrients in sap for the first study period (2018–2019). Uncertainties include both those type B associated to the measurement procedure and those type A linked to the sample variability. Both were added quadratically. Uncertainty bars correspond to a coverage factor k = 1.

Ca and Mg showed similar dynamics in sap, with a decrease from June to December and an increase in the first months of the year, with magnesium concentrations increasing more sharply than calcium.

Micronutrients, including Mn, Cu, and Zn, had high initial concentrations (April-June 2018), followed by a gradual decline into early 2019. Cu concentrations ranged from 0.2 to 0.6 ppm, Zn concentrations ranged from 0.1 ppm, and Mn concentrations remained low (<0.05 ppm).

The concentrations of chloride, sulfate, and Na were higher in the last three trimesters of 2019, whereas B showed an increase during the second trimester of 2018 and a significant decrease by early 2019.

Soil, Leaf, and Sap Data From the Two Study Periods (2018–2019 and 2022–2024)

The second period of study (2022–2024) showed comparisons of pH and electrical conductivity (EC) of soil and sap (**Figure 4**). pH in soil was significantly higher in Osuna during this period, whereas EC showed no significant differences across the two periods, although larger standard deviations were observed in Luenga, Guadiana, and Osuna.

In sap, EC was more stable, with smaller deviations, except for Guadiana in the second period (2022–2024). As shown in **Figure 4**, pH values are higher in the first study period (2018–2019). However, the EC shows the higher values in the second study period (2022–2024).

The concentrations of P, K, Ca, and Mg showed no significant differences between the two periods, except for P in Luenga and K in Fuensanta. However, the mean values of these nutrients in both soil and sap were generally higher in the second period (2022–2024, **Figure 5**).

Despite differences in soil and leaf concentrations, the sap and leaf concentrations of these elements were similar across both periods. For example, in Luenga and Guadiana, which had high concentrations of $CaCO_3$ or clay content in their soils, there were higher soil levels of P and K, but no corresponding increase in sap and leaf concentrations. This finding highlights the role of soil texture and carbonates in nutrient availability.

Micronutrients in Soil, Leaf, and Sap

The micronutrient concentrations of Mn, Cu, and Zn in soil, sap, and leaves were considerably different, with the highest

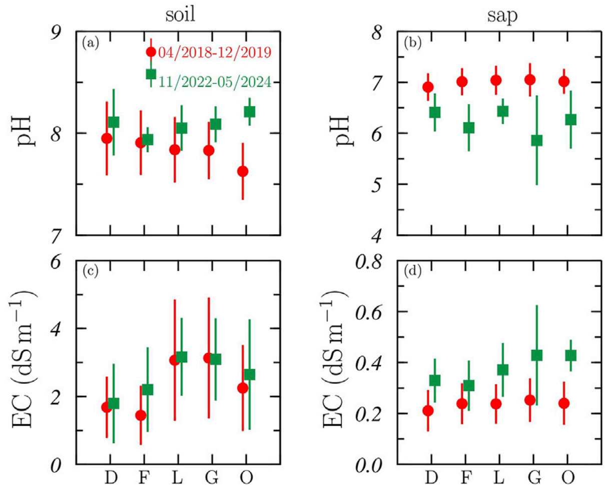

FIGURE 4 | Comparison of pH and electrical conductivity between soil and sap on the five farms selected for the two study periods (2018–2019 and 2022–2024). D: Dílar, F: Fuensanta, L: Luenga, G: Guadiana, O: Osuna. Labels **a**, **c** correspond to soil and **b**, **d** to sap.

concentrations observed in leaves (Zn up to 20 ppm), lower concentrations in soil (max. 12 ppm), and much lower concentrations in sap (0.1 ppm) (**Figure 6**). The standard deviations were larger for soil concentrations in the first study period (2018–2019).

In sap, the standard deviations were more pronounced during the second period (2022–2024), especially for Cu and Zn, whereas the differences between periods were less significant for Mn and Zn in leaves. These differences are linked to the management of fertilization practices, especially for micronutrients, and changes in environmental factors, such as precipitation and irrigation quality.

DISCUSSION

To understand plant nutrition in general, and olive tree nutrition in particular, it is essential to understand the availability of nutrients in the soil, their concentration in the leaves, and the mobility of elements in the sap. The transport of water and solutes in the tree occurs through the xylem and phloem systems (White and Ding, 2023). Differentiating between xylem and phloem is not straightforward because the exchange of solutes between them is crucial for regulating long-distance transport (White and Ding, 2023). Therefore, comparing the evolution of nutrient concentrations in the soil and leaf is fundamental to understanding what happens in the sap and the overall nutrition of trees.

The pH in sap is very stable, and although it is sensitive to changes related to the application of different anions or cations, these changes are small and quickly reversed (Larbi et al., 2003). In this study, the pH of sap was higher in the first study period (2018–2019) than in the second period (2022–2024), although the values were around 7. In contrast, electrical conductivity was higher in the second study period (2022–2024), coinciding with a drop in pH (with minimum values of pH reaching 5.5) at times. The continued decrease in precipitation from the first (2018–2019) to the second study period (2022–2024) forced farmers to reduce irrigation doses and use lower-quality water. Additionally, some farmers added amino acids and algae as supplementary treatments to strengthen the trees against drought. This also explains the changes in pH and electrical conductivity in soil, which is also a buffered medium (Porta et al., 1999).

The evolution of leaf and sap nutrients was estimated during the first study period (2018–2019), when precipitation was abundant and the trees were in full production. This allowed the study of changes in nutrient concentrations throughout the activity periods of the plantations. The relationship between sap conduction and periods of drought has been reported in other studies (Terral et al., 2025).

The evolution of leaf nutrients studied in 2018 was repeated without significant differences in the same quarters of 2019. The yields during these 2 years (data not presented) were very similar. Some elements such as P, B, and K show different dynamics compared to those observed by other authors (Fernández-Escobar et al., 1999; Nieto et al., 2017). However, other elements such as N, Mg, Ca, Mn, and Zn maintain the same dynamics. This is primarily due to changes in olive fertilization management in recent years. For instance, for N, the evolution of its concentration in leaves has not changed because it was the element that was most carefully applied and dosed. Other elements like K or P no longer decrease in concentration throughout the year, as previously indicated in earlier studies, but their concentrations remain high in leaves for most of the year, with dynamics similar to those of N. On one hand, K plays a fundamental role in nitrate transport in the xylem (Van Beusichem et al., 1988; White, 2012), which is evident in our study by the high similarity of N and K dynamics in leaves (**Figure 2**); on the other hand, these nutrients are currently applied in various and continuous ways: to the soil, in the center of the row, as foliar fertilizers in March, May, June, and December, and in small doses via fertigation throughout most of the year. Additionally, foliar applications prevent K sequestration by soil colloids, especially clays, enhancing its immediate availability throughout the year (Rodrigues et al., 2012). Similarly, studies that have increased P application in the soil have frequently concluded that there is no response from trees or production to these additions (Fernández-Escobar et al., 2017). The type of soil plays a crucial role in this element (Porta et al., 1999). In this study, the farm with the lowest K and P values in the soil (Osuna) also had the lowest concentrations of both sap and leaves during both study periods (**Figure 5**). However, very high K and P values in the soil, as seen in Luenga and Guadiana (**Table 2**; **Figure 5**), do not correlate with higher concentrations in sap and leaves (**Figure 5**). The high $CaCO_3$ and/or clay content in these three farms (**Table 2**) were the factors highlighted by various authors to explain the availability of these elements. Recently, other

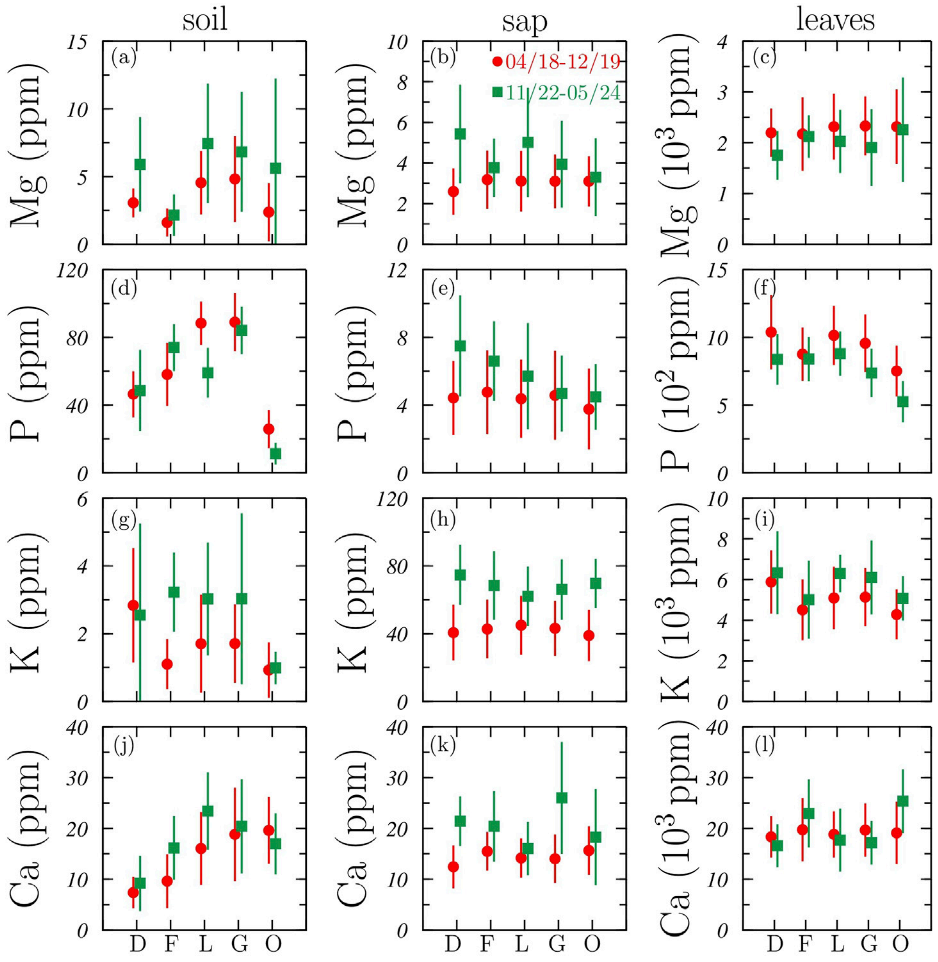

FIGURE 5 | Levels of Mg, P, K, and Ca detected in the three media for the five selected farms in the two study periods. D: Dílar, F: Fuensanta, L: Luenga, G: Guadiana, O: Osuna. Labels **a**, **d**, **g**, **j** correspond to soil concentrations of the above elements; **b**, **e**, **h**, **k** to sap concentrations; **c**, **f**, **i**, **l** to leaves concentrations. Uncertainties include both those type B associated to the measurement procedure and those type A linked to the sample variability. Both were added quadratically. Uncertaintys bars correspond to a coverage factor k = 1.

authors (Ferreira et al., 2018) have reported that when experiments are carried out in inert substrates, a response to P application in the soil is observed.

One element that well reflects this management change is B, whose evolution in previous studies has been described as a progressive decrease in leaf concentration with age, moving toward flowers and fruit (Nieto et al., 2017). However, it is now commonly applied as complexes of B, Mg, and S or as sodium borate via foliar application, which maintains more stable concentrations of B, S, and Na (**Figure 2**). The three elements had their lowest concentrations in January, February, and March of 2019 (point 4, **Figure 2**) and in the following quarter of both years (points 1 and 5, **Figure 2**), after harvest, and before the spring foliar application. The transport of B from the leaf to the fruit has been noted by several authors (Rodrigues et al., 2012; Başar and Gürel, 2016).

Ca and Mg have not changed their application as fertilizers or alongside other fertilization practices, and they share similar dynamics throughout both study periods. These elements had the highest concentrations in leaves and sap, as well as in soils where their concentrations were also higher (**Figure 5**; **Table 2**), such as Luenga (L), Guadiana (G), and Osuna (O). No significant differences were observed between the two study periods for either element, but in general, the standard deviations were higher in the second period (2022–2024, **Figure 5**), especially on the three previously mentioned farms, likely due to differences in precipitation and irrigation water quality during the two periods on these farms.

The availability of Fe, Mn, Cu, and Zn is influenced by soil characteristics such as pH and calcium carbonate content (Marschner, 1993). The dynamics of these elements are very similar to each other (**Figure 2**) and, in general, higher in the second study period (2022–2024) in leaves, and especially in sap (**Figure 6**), compared to the first period (2018–2019). Başar and Gürel (2016) noted that these micronutrients, particularly Zn, are transferred from the leaf to the fruit, which could explain the decrease in Zn concentration in leaves in the third and fourth quarters of both years, when the fruit requires it most (**Figure 2**).

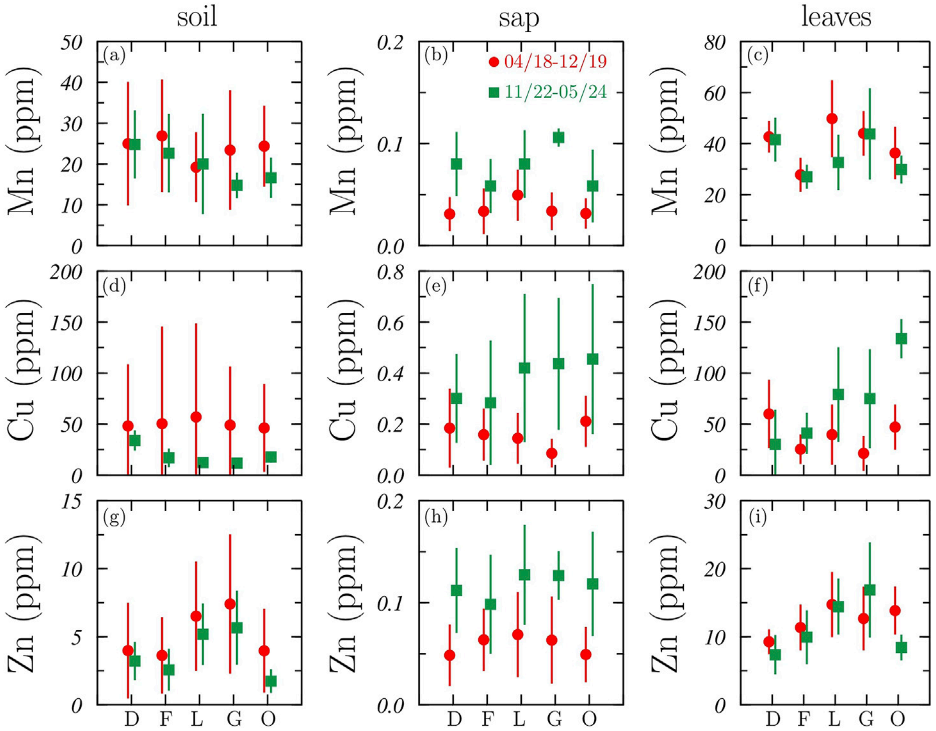

FIGURE 6 | Microelement concentrations (Mn, Cu and Zn) in the three media analyzed in the five farms for the two study periods (2018–2019 and 2022–2024). D: Dílar, F: Fuensanta, L: Luenga, G: Guadiana, O: Osuna. Labels **a**, **d**, **g** correspond to soil concentrations of the above elements; **b**, **e**, and **h** to sap; **c**, **f**, **i** to leaves. Uncertainties include both those type B associated to the measurement procedure and those type A linked to the sample variability. Both were added quadratically. Uncertainty bars correspond to a coverage factor k = 1.

This would also explain the decreases in Mn and Zn in the leaves and the increase in sap during the same period (**Figure 6**). Furthermore, the similarity in Cu dynamics in both years (**Figure 6**), which is only applied to leaf and sap, seems to confirm these results.

The correlations between nutrient concentrations, pH, and EC in leaf, sap, and soil are presented in **Supplementary Figures S1–S3** (**Supplementary Material**). In general, the most frequent correlations are observed within the same matrix (leaf-to-leaf, sap-to-sap and soil-to-soil), especially in sap. Nutrient correlations between sap and soil are positive but statistically insignificant ($R^2 < 0.5$). Additionally, the correlations between pH, EC, Mn, and Cu in soil are negative with respect to other elements, both in soil and sap.

These results are likely influenced by the sampling design, where fertilization practices by farmers were not considered. A study with more rigorously controlled conditions would likely yield more robust correlations.

CONCLUSION

In order to know the nutrition of olive trees and to carry out a fertilisation that generates an adequate production while protecting the environment, it is convenient to know the availability of nutrients in the soil, their concentration in the leaves and the mobility of the elements in the sap. Water and nutrients in the sap are transported from the soil by the xylem and then distributed through the phloem according to the nutritional needs related to the phenological stages of the tree.

The dynamics of the concentrations of many elements in leaf and sap, for example, phosphorus, potassium, calcium or magnesium, follow inverse patterns: in periods when concentrations are increasing in the leaves, they are decreasing in the sap and *vice versa*, as corresponds to a transport medium such as the sap and a nutrient store such as the leaf.

Nutrient concentrations in soil, leaf and sap varied seasonally with tree phenology, fertiliser application and climate. Nutrient concentrations in leaf were higher than in soil and in soil higher or equal than in sap, except for K, the most abundant element in sap, with concentrations exceeding those in soil.

In the first study period (2018–2019) values with smaller standard deviations were observed than in the second study period (2022–2024). Low rainfall and poor irrigation water quality affected the availability and mobility of nutrients. Elements that are not usually applied as fertilisers, such as Ca and Mg, showed higher stability in the two study periods.

Tree sap showed sensitivity to changes in nutrient concentrations. These results indicate that sap extraction using a modified Scholander-Hammel chamber is an effective method for providing additional information to foliar and soil analyses. Therefore, it can contribute to improving the determination of the nutritional status of the olive tree.

DATA AVAILABILITY STATEMENT

The data used in this study are available on demand. Requests to access the datasets should be directed to antagarc@ugr.es.

AUTHOR CONTRIBUTIONS

All authors listed have made a substantial, direct, and intellectual contribution to the work and approved it for publication.

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CONFLICT OF INTEREST

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

GENERATIVE AI STATEMENT

The author(s) declare that no Generative AI was used in the creation of this manuscript.

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SUPPLEMENTARY MATERIAL

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REFERENCES

Abid, M., and Lal, R. (2008). Tillage and Drainage Impact on Soil Quality-I. Aggregate Stability, Carbon and Nitrogen Pools. *Soil till. Res.* 1, 89–98. doi:10.1016/j.still.2008.04.012

Aguilera-Huertas, J., Parras-Alcántara, L., González-Rosado, M., and Lozano-García, B. (2022). Medium-Term Evaluation of the 4‰ Initiative, Soil Organic Carbon Storage and Stabilisation in a Mediterranean Rainfed Olive Grove under Conventional Tillage: A Case Study. *Environ. Res.* 215, 114382. doi:10.1016/j.envres.2022.114382

Bacelar, A. U., Moutinho-Pereira, J. M., Gonçalves, B. C., Ferreira, H. F., and Correia, C. M. (2007). Changes in Growth, Gas Exchange, Xylem Hydraulic Properties and Water Use Efficiency of Three Olive Cultivars under Contrasting Water Availability Regimes. *Environ. Exp. Bot.* 60 (2), 183–192. doi:10.1016/j.envexpbot.2006.10.003

Başar, H., and Gürel, S. (2016). The Influence of Zn, Fe and B Applications on Leaf and Fruit Absorption of Table Olive "Gemlik" Based on Phonological Stages. *Sci. Horti.* 198, 336–343. doi:10.1016/j.scienta.2015.12.001

BOJA (2008). Reglamento específico de producción integrada de olivar. (in Spanish). Available online at: https://juntadeandalucia.es/boja/2008/83/2. (Accessed September, 2024).

Cabañero, F. J., and Carvajal, M. (2007). Different Cation Stresses Affect Specifically Osmótica Root Hydraulic Conductance, Involving Aquaporins, ATPase and Xylem Loading of Ions in *Capsicum Annuum. L. Plants. J. Plant Physiol.* 164, 1300–1310. doi:10.1016/j.jplph.2006.08.010

Carella, P., Wilson, D. C., Kempthorne, C. J., and Cameron, R. K. (2016). Vascular Sap Proteomics: Providing Insight into Long-Distance Signaling during Stress. *Front. Plant Sci.* 7, 651–658. doi:10.3389/fpls.2016.00651

Do Amarante, L., Lima, J. D., and Sodek, L. (2006). Growth and Stress Conditions Cause Similar Changes in Xylem Amino Acids for Different Legume Species. *Environ. Exp. Bot.* 58 (1-3), 123–129. doi:10.1016/j.envexpbot.2005.07.002

Domouso, P., Calero, J., Ruiz-Cátedra, G., and García-Ruiz, R. (2024). Nitrogen Recycling across a Spectrum of Fertilization Strategies: An Assessment in Olive Groves. *Agr. Ecosyst. Environ.* 372, 109096. doi:10.1016/j.agee.2024.109096

El Yamani, M., and Cordovilla, M. D. P. (2024). Tolerance Mechanisms of Olive Tree (Olea Europaea) under Saline Conditions. *Plants* 13, 2094. doi:10.3390/plants13152094

Espejo-Pérez, A. J., Rodríguez-Lizana, A., Ordóñez, R., and Giráldez, J. V. (2013). Soil Loss and Runoff Reduction in Olive-Tree Dry-Farming with Cover Crops. *Soil Sci. Soc. Am. J.* 77, 2140–2148. doi:10.2136/sssaj2013.06.0250

Esteves, E., Locatelli, G., Bou, N. A., and Ferrarezi, R. S. (2021). Sap Analysis: A Powerful Tool for Monitoring Plant Nutrition. *Horticulturae* 7, 426. doi:10.3390/horticulturae7110426

Fernández-Escobar, R., Barranco, D., Fernández-Escobar, R., and Rallo, L. (2017). *El Cultivo del Olivo*. 7th ed. (Madrid, Spain: Mundi-Prensa), 419–460.

Fernández-Escobar, R., García-Novelo, J. M., and Restrepo-Díaz, H. (2011). Mobilization of Nitrogen in the Olive Bearing Shoots after Foliar Application of Urea. *Sci. Horti.* 127 (3), 452–454. doi:10.1016/j.scienta.2010.10.006

Fernández-Escobar, R., Moreno, R., and García-Creus, M. (1999). Seasonal Changes of Mineral Nutrient in the Olive Leaves during the Alternate-Bearing Cycle. *Sci. Horti.* 82, 25–45. doi:10.1016/S0304-4238(99)00045-X

Ferreira, I. Q., Ângelo Rodrigues, M. Â., Moutinho-Pereira, J. M., Correia, C. M., and Arrobas, M. (2018). Olive Tree Response to Applied Phosphorus in Field and Pot Experiments. *Sci. Horti.* 234, 236–244. doi:10.1016/j.scienta.2018.02.050

García-Orenes, F., Roldán, A., Mataix-Solera, J., Cerdà, A., Campoy, M., Arcenegui, V., et al. (2012). Soil Structural Stability and Erosion Rates Influenced by Agricultural Management Practices in a Semi-Arid Mediterranean Agro-Ecosystem. *Soil Use Manag.* 28, 571–579IOC. doi:10.1111/j.1475-2743.2012.00451.x

Guérin, V., Huché-Thélier, L., and Charpentier, S. (2007). Mobilisation of Nutrients and Transport via the Xylem Sap in a Shrub (*Ligustrum Ovalifolium*) during Spring Growth: N and C Compounsds and Interactions. *J. Plant Physiol.* 164, 562–573. doi:10.1016/j.jplph.2006.03.012

IBM Corp (2010). *IBM SPSS Statistics for Windows, Version 19.0*. Armonk, NY: IBM Corp.

IOC (2003). Madrid, Spain: International Olive Council. Available online at: https://www.internationaloliveoil.org (Accessed September, 2024).

IOC (2022). Madrid, Spain: International Olive Council. Available online at: https://www.internationaloliveoil.org (Accessed September, 2024).

IUSS Working Group WRB (2022). "World Reference Base for Soil Resources," in *International Soil Classification System for Naming Soils and Creating Legends for Soil Maps*. 4th ed. Vienna, Austria: International Union of Soil Sciences. IUSS.

Junta de Andalucía (2016). The Integrated Olive Production Regulation in Andalusia. Available online at: https://www.juntadeandalucia.es/organismos/agriculturapescaaguaydesarrollorural/areas/agricultura/sanidad-vegetal/paginas/produccion-integrada-regl-oli.html (Accessed September 2024).

Larbi, A., Morales, F., Abadía, A., and Abadía, J. (2010). Changes in Iron and Organic Acid Concentrations in Xylem Sap and Apoplastic Fluid of Iron-Deficient *Beta Vulgaris* Plants in Response to Iron Resupply. *J. Plant Physiol.* 167 (4), 255–260. doi:10.1016/j.jplph.2009.09.007

Larbi, A., Morales, F., Abadía, J., and Abadía, A. (2003). Effects of Branch Solid Fe Sulphate Implants on Xylem Sap Composition in Field-Grown Peach and Pear: Changes in Fe, Organic Anions and pH. *J. Plant Physiol.* 160, 1473–1481. doi:10.1078/0176-1617-01010

Lima, F., Blanco-Sepúlveda, R., Calle, M., and Andújar, D. (2023). Reconstruction of Historical Soil Surfaces and Estimation of Soil Erosion Rates with Mound Measurements and UAV Photogrammetry in Mediterranean Olive Groves. *Geoderma* 440, 116708. doi:10.1016/j.geoderma.2023.116708

Marschner, H. (1993). "Zinc Uptake from Soils," in *Zinc in Soils and Plants*. Editor A. D. Robson (Dordeecht, Netherlands: Kluwer Academic Publishers), 59–77.

Ministerio de Agricultura, Pesca y Alimentación (1994). *Métodos Oficiales de Análisis. III*. Madrid: Ministerio de Agricultura, Pesca y Alimentación.

Morgado, R., Flores Ribeiro, P., Lima Santos, J., Rego, F., Beja, P., and Moreira, F. (2022). Drivers of Irrigated Olive Grove Expansion in Mediterranean Landscapes and Associated Biodiversity Impacts. *Landsc. Urban Plan.* 225, 104429. doi:10.1016/j.landurbplan.2022.104429

Morgado, R., Santana, J., Porto, J. M., Sánchez-Oliver, S., Reino, L., Herrera, J. M., et al. (2020). Mediterranean Silent Spring? The Effects of Olive Farming Intensification on Breeding Bird Communities. *Agr. Ecosyst. Environ.* 288, 106694. doi:10.1016/j.agee.2019.106694

Nieto, J., García-Fuentes, A., García, L. M., and Fernández-Ondoño, E. (2017). Estudio de la dinámica nutricional en hojas de olivo: Periodos de estabilidad analítica. *Span. J. Soil Sci.* 7, 40–58. doi:10.3232/SJSS.2017.V7.N1.04

Porta, J., López-Acebedo, M., and Poch, R. M. (2008). "Introducción a la Edafología," in *Uso y Protección del Suelo*. Madrid, Spain: Mundi-Prensa, 451.

Porta, J., López-Acebedo, M., and Roquero, C. (1999). Edafología para la agricultura y el medio ambiente. *2^{a} Edición. Mundi-Prensa*, 849.

Quevauviller, Ph., Lachica, M., Barahona, E., Rauret, G., Ure, A. M., Muntau, H., et al. (1998). Certified Reference Material for the Quality Control of EDTA- and DTPA-Extractable Trace Metal Contents in Calcareous Soil (CRM 600). *Fresenius J. Anal. Chem.* 360, 505–511. doi:10.1007/s002160050750

R Development Core Team (2017). *R: A Language and Environment for Statistical Computing*. Vienna, Austria: R Found. Stat. Comput. Available online at: https://www.R-project.org/.

RIA (2024). Red de Información Agroclimática de Andalucía. Available online at: https://www.juntadeandalucia.es/agriculturaypesca/ifapa/riaweb/web/ (Accessed July 7, 2024).

Rodrigues, M. Â., Ferreira, I. Q., Claro, A. M., and Arrobas, M. (2012). Fertilizer Recommendations for Olive Based upon Nutrients Removed in Crop and Pruning. *Sci. Hortic.* 142, 205–211. doi:10.1016/j.scienta.2012.05.024

Rousseaux, M. C., Figuerola, P. I., Correa-Tedesc, G., and Searles, P. S. (2009). Seasonal Variations in Sap Flow and Soil Evaporation in an Olive (*Olea Europaea* L.) Grove under Two Irrigation Regimes in an Arid Region of Argentina. *Agric. Water Manag.* 96 (6), 1037–1044. doi:10.1016/j.agwat.2009.02.003

Sastre, B., Barbero-Sierra, C., Bienes, R., Marques, M. J., and García-Díaz, A. (2017). Soil Loss in an Olive Grove in Central Spain under Cover Crops and Tillage Treatments, and Farmer Perceptions. *J. Soils Sediment.* 17, 873–888. doi:10.1007/s11368-016-1589-9

Soil Conservation Service (1972). "Soil Survey Laboratory Methods and Procedures for Collecting Soils Samples," in *Soil Surv. Report 1* (Washington, DC, USA).

Sutton, M. A., Bleeker, A., Howard, C. M., Bekunda, G., de Vries, W., van Grinsven, H. J. M., et al. (2013). Our Nutrient World: The Challenge to Produce More Food and Energy with Less Pollution Global Overview of Nutrient Management. *Centre Ecol. and Hydrology*.

Terral, J. F., Creusot, P., Limier, B., Ivorra, S., Bombeau, A., Bernazeau, B., et al. (2025). The Potential of Sap Conduction in the Olive Tree Is Linked to Aridity Conditions of the Main Cultivation Area of Varieties and Allow to Uncover Their Sensitivity to Ongoing Climate Change. *Sci. Hortic.* 339, 113856. doi:10.1016/j.scienta.2024.113856

Tyurin, I. V. (1951). Analitical Procedure for a Comparature Study of Soil Humus. *Tr. Pochr. Inst. Dokuchaev* 33, 5–21.

U.S. Salinity Laboratory Staff (1954). *Diagnosis and Improvement of Saline and AlkaliSoils, Handbook 60*. Washington, DC: US Department of Agriculture, 160.

Van Beusichem, M. L., Kirkby, E. A., and Baas, R. (1988). Influence of Nitrate and Ammonium Nutrition and the Uptake, Assimilation, and Distribution of Nutrients in *Ricinus communis*. *Plant Physiol.* 86, 914–921. doi:10.1104/pp.86.3.914

Watanabe, F. S., and Olsen, S. R. (1965). Test of an Ascorbic Acid Method for Determining Phosphorus in Water and $NaCO_3H$ Extracts from Soils. *Soil Sci. Soc. Am. Proc.* 29, 677–678. doi:10.2136/sssaj1965.03615995002900060025x

Weinbaum, S. A., Johnson, R. S., and De Jong, T. M. (1992). Causes and Consequences of Overfertilization in Orchards. *Hort. Technol.* 2, 112–121. doi:10.21273/horttech.2.1.112b

White, P. J. (2012). "Chapter 3 - Long-Distance Transport in the Xylem and Phloem," in *Marschner's Mineral Nutrition of Higher Plants*. 3rd ed. (Academic Press), 49–70. doi:10.1016/B978-0-12-384905-2.00003-0

White, P. J., and Ding, G. (2023). "Chapter 3 - Long-Distance Transport in the Xylem and Phloem," in *Marschner's Mineral Nutrition of Plants* (© Elsevier Ltd.), 73–104. doi:10.1016/B978-0-12-819773-8.00002-2

ORIGINAL RESEARCH
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Shrub Control by Burning and Clearing in the Southern Pyrenees: Effects on Soils After Two Years of Treatment

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Prescribed burns and selective shrub clearing are widely implemented as management strategies to stop the shrub encroachment of grasslands, decrease fuel loads and fire risks, and improve biodiversity and ecosystem functionality in mountain environments. While the short-term effects of burns on soil have been extensively studied, the impact of mechanical treatments on soil has received comparatively less attention. This study aims to: i) evaluate the physical, chemical, and biological characteristics of subalpine soils influenced by prescribed burns and selective clearing, and ii) assess the effectiveness of these interventions by examining the changes in vegetation cover 2 years after implementation. The research was conducted in the Central Pyrenees, where three plots were selected according to their management type: a prescribed burn plot (B), a clearing plot (CL), and a shrubland control plot (C). The results highlight how both treatments increased soil pH and reduced other properties (EC, BD, moisture, GLU) after 2 years of study, with burned and cleared plots showing similar trends in all cases. The carbon source utilization patterns of soil microbial communities (CLPP) remained unchanged by either treatment, which may indicate the short-term resilience of microbial communities. However, differences in soil microbial activity, as measured by basal soil respiration (bSR), were observed. An increase in bSR was found with shrub removal via mechanical clearing, as evidenced by the constants of the single-compartment model and the average residence time (ART) of organic matter. These changes were primarily driven by the indirect effects of vegetation cover alteration. Shrub cover remained low 2 years after the application of both methods, although prescribed burning resulted in more bare soil and lower plant diversity compared to the cleared plot.

Keywords: basal soil respiration, CLPP, glomalin, biodiversity, shrub management

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INTRODUCTION

Grassland communities in mountain areas, one of the most important ecosystems for plant diversity, are being replaced by expanding shrubland due to land-use changes driven by a decline in grazing pressure, resulting from rural depopulation and land abandonment (Schirpke et al., 2017; Tokarczyk, 2017; Lasanta, 2019). This issue is part of Global Change, alongside vegetation cover transformations and climate changes linked to global warming. These processes negatively impact natural mountain ecosystems, leading to irreversible changes in ecosystem functionality and services, alterations in landscape primary productivity, reductions in biodiversity, and changes in soil and vegetation properties (Alados et al., 2019; Vadillo et al., 2023).

Woody encroachment on former pastures is especially suitable in the Pyrenees where it is estimated that 2/3 have been affected in recent decades (Gelabert et al., 2021). Among these bushes stands *Echinospartum horridum* (Vahl) Rothm, a spiny, cushion-shaped species, endemic to the Pyrenees. This species is strictly calcicolous, well-adapted to dry air, intense sunlight, stony and shallow soils, and is highly resistant to grazing (Montserrat et al., 1984). Its expansion is prominent in the Pre-Pyrenean mountains and the central Pyrenees of Aragón, preferably on south facing slopes, where it forms large, dense, monotypic stands that can cover several hectares (Mora et al., 2022; Komac et al., 2011). Moreover, there is higher seedling survival of this species after burns. Fires kill the plant but trigger the simultaneous germination of seeds (Montserrat et al., 1984). Alados et al. (2019) compared clearing vs burning treatments for restoring subalpine grasslands after shrub encroachment in Tella (Pyrenees); they found, 5 years after treatment, as burn had higher *E. horridum* cover and abundance (more than double) than clear cut treatment.

Historically, fire has been used as a management tool to control shrub expansion and promote grassland regeneration. However, selective shrub clearing is being used as an alternative measure that not only reduces fuel build-up and the risk of summer wildfires but also helps conserve the diversity and functionality of mountain ecosystems (Alados et al., 2019; Fontúrbel et al., 2016; Castillo-Garcia et al., 2024; Pereira et al., 2023). Many studies also propose integrating these management strategies with pyric herbivory, a traditional practice which combines fire and guided grazing. This approach is considered a potentially more effective strategy for mitigating grassland shrub encroachment and promoting plant species diversity (Alados et al., 2019; Cortijos-López et al., 2023). It is also important to include rest periods between herbivory treatments, as grazing animals may consume the regrowth of desired species, delaying recovery. However, other studies have shown that continuing with current control and grazing practices will not achieve pastures typical of the Central Pyrenees due to the reduced livestock density within these ecosystems. Therefore, it is still necessary to implement additional strategies to prevent shrub encroachment in pastures (Cottani and Sabattini, 2006; San Emeterio et al., 2016; Amsten et al., 2024; Clarke et al., 2013; Mora et al., 2022).

It has been demonstrated that mechanical clearing practices promote an increase of soil organic carbon storage, acting as carbon sinks as shrub clearing process increases the soil organic carbon (SOC) about 40% compared to shrubland cover (Cortijos-López et al., 2023; Nadal-Romero et al., 2018; 2021; Berninger et al., 2015). During the initial stage of woody invasion in the grasslands of the subalpine zone of the Central Spanish Pyrenees, the SOC stock in the mineral fraction decreases by 38%, from 147.9 Mg C/ha to 91.7 Mg C/ha, due to reduced carbon inputs from herbaceous vegetation and alterations in the decomposition and stabilization processes of soil carbon. Over time, as woody vegetation becomes established and matures, SOC stocks may recover or even increase due to new organic matter contributions from shrub and tree vegetation (Nadal-Romero et al., 2018). Furthermore, it has been shown that clear cutting can modify soil microbial communities in the long term (Hynes and Germida, 2013). Initially, microbial communities may thrive due to the decomposition of roots, but over time, the availability of these nutrients declines, leading to a reduction in microbial biomass growth rates. Additionally, mechanical clearing has been shown to increase soil temperature (Hashimoto and Suzuki, 2004), with associated modifications on the biological community and soil properties.

The effects of burning practices on soil are highly variable and depend on numerous factors, including climate, type and amount of fuel, fire intensity, duration, size of the burned area, time since the last fire, fire history, soil type, moisture content, and slope (Bodí et al., 2014). Among these, fire duration is one of the most impactful characteristics: longer fires result in greater soil impacts (Alfaro-Leranoz et al., 2024). Even low-temperature fires can reduce microbial biomass and soil respiration (Francos et al., 2018), affecting the diversity and structure of microbial communities. This is particularly important because soil bacterial communities play a critical role in edaphic structure and ecosystem recovery following disturbances. Microorganisms contribute significantly to ecosystem regeneration and recovery (Moya et al., 2022; Fontúrbel et al., 2024). However, in general, bacteria tend to be more resilient to post-fire edaphic conditions than fungi (De la Rosa et al., 2014). During the first month after a fire, fungal populations decrease significantly and take a long time to recover to pre-fire levels, largely due to the loss of soil organic matter caused by the fire. The destruction of soil mycological flora has severe consequences for vegetation, as the lack of mycorrhizae reduces plants' ability to absorb water and nutrients (Martínez et al., 2006; Fernández de Ana-Magán, 2000). In the Central Pyrenees, numerous studies have already been conducted on the impact of prescribed burns on various soil properties (Armas-Herrera et al., 2016; Girona-García, et al., 2018; Alfaro-Leranoz, et al., 2023). Among the findings, a decrease in β-D-glucosidase (GLU) activity was observed immediately after the burn, and this activity does not recover over time. In contrast, other properties did not show an immediate reduction but experienced declines over time, such as total soil organic carbon (SOC), labile carbon (DOC), total nitrogen (TN), and basal soil respiration (bSR).

These two management practices produce both direct and indirect effects on the soil, highlighting the importance of distinguishing between them. In the case of burns, direct effects are a result of the temperatures reached during the fire and the combustion process of surface biomass and organic matter. Indirect effects are associated with the post-treatment period following both fire and mechanical clearing. During this time, changes in ecosystem components, such as the reduction of vegetation and litter cover, the presence of ash and burned plant material (in the case of burns), or shredded plant material (in the case of clearing), influence soil microbial populations and, consequently, edaphic characteristics and vegetation recovery (Santín and Doerr, 2016; Zavala et al., 2014; Bodí et al., 2014).

While numerous studies have focused on the single effects of prescribed fire on soil, particularly in the immediate aftermath

FIGURE 1 | Location of the area of study (Asín de Broto, NE-Spain). Scale: 1:10,000.

(Fontúrbel et al., 2024; Girona-García et al., 2019; Agbeshie et al., 2022; González-Pérez et al., 2004) and clearing effects on soil and vegetation response (Pietikäinen and Fritze, 1995; Alados et al., 2019), there is limited information comparing the effects of mechanical treatments and prescribed burns, especially about soil properties. The aim of this study is to evaluate the effects of key management practices on mountain pasture ecosystems 2 years after their implementation. Specifically, the objectives are: i) to characterize the physical, chemical, and biological properties of soils in mountain pastures subjected to different management treatments, and ii) to assess the effectiveness of these treatments by analyzing changes in vegetation cover over time in the experimental plots.

Two years after the application of both treatments, ashes had either been leached or incorporated into the soil, similar to the behavior of shredded plant material. However, large-sized burned vegetation, such as mature *E. horridum* remains in the ecosystem due to its robust shrub structure with thick trunks and branches. Consequently, assessing the effects of fire and mechanical clearing primarily relies on indirect measurements of changes in soil properties and vegetation cover.

This study hypothesizes that no significant differences will be observed in the physical, chemical, and biological properties of the soils 2 years after the implementation of the two *E. horridum* management treatments (prescribed burning and mechanical clearing) as previous studies on prescribed burns have shown that the effects of fire on soil are typically confined to the top centimeter of the soil profile. Additionally, it is expected that the regeneration of *E. horridum* will be differently affected by the management treatments, with lower cover observed in the prescribed burn treatment compared to other treatments, because of fire on vegetation.

MATERIALS AND METHODS

Experimental Design and Treatments

The study area is in a subalpine mountain passes in Asín de Broto (Sobrarbe, Huesca, Spain) (**Figure 1**). The climate is characterized by a mean annual temperature of 8.8°C and an average annual precipitation of 1,120 mm/year (Girona-García et al., 2019). The slope faces west, with an inclination between 10% and 15%. The most common soils in this area correspond to Eutric Cambisols and Calcaric Cambisols (IUSS Working Group WRB, 2022), developed over Eocene turbidites (IGME, 1972). Non-shrub grasslands in this area are classified as priority habitat 6,210, “Semi-natural dry grasslands and scrubland facies on calcareous substrates (*Festuco-Brometalia*)” (Girona-García et al., 2019).

Three plots were selected in this area (**Figure 2**) at elevations ranging from 1,606 to 1,644 m a.s.l., according to their management practices: one subjected to a prescribed burn in 2021 (B) covering 0.38 ha, another subjected to mechanical clearing in the same year (CL) covering 1.28 ha, and a control plot (C) of 0.77 ha situated between the other two, where no interventions were conducted and shrub dominance persists.

Prior to the interventions, both managed plots were dominated by *E. horridum*. Prescribed burning was performed when the environmental conditions met the prescribed parameters set by firefighters of the EPRIF (Wildfire Prevention Team) of Huesca and BRIF (Reinforcement Brigades against Wildfires) of Daroca units. Similar burns (Girona-García et al., 2018; Alfaro-Leranoz et al., 2023) result in temperatures of 812°C at the soil surface, which decrease at ambient temperature below 2 cm depth. Despite this, the litter layer was not completely consumed by the fire. Following the treatments, the soil was covered with biomass remains from burning and clearing, with the cleared residue reaching a thickness of 4 cm.

The study area was also subject to continuous, free grazing across approximately 100 ha, including the three study plots. The grazing regime is as follows: cattle grazing occurred from 20 April to 2 July, with a load of 100 cows, and from 1 November to 1 January, with a reduced load of 40 cows. Sheep grazing was more extensive, with 1,500 sheep present from April to 21 July, followed by 500 sheep grazing from July to September. From September to November, sheep numbers started at 1,300 and decreased gradually, with 15 fewer sheep per day until the end of the period. Additionally, 20 goats grazed year-round, except from October to December, while a single donkey grazed concurrently with the sheep.

Vegetation Monitoring and Soil Sampling

To assess the effectiveness of the management treatments in promoting vegetation recovery and to evaluate vegetation structure and species composition, a total of four 15-m transects were established in each plot. Vegetation cover was measured at consistent intervals of 10 cm along the entire length of each transect, ensuring detailed and uniform data collection across all plots. Cover was established using the Line-Intercept Sampling method (Cummings and Smith, 2000; Eberhardt, 1978) and categorized into four functional groups: grasses, legumes, *E. horridum* (thorny cushion), other species, and bare soil, or litter. Additionally, four litter samples were collected from 30 × 30 cm quadrats along each transect in the cleared and burned plots to quantify the litter present on the surface of each plot (kg/ha).

FIGURE 2 | Location of the treatment plots: Control (C), Burned (B) and Cleared (CL).

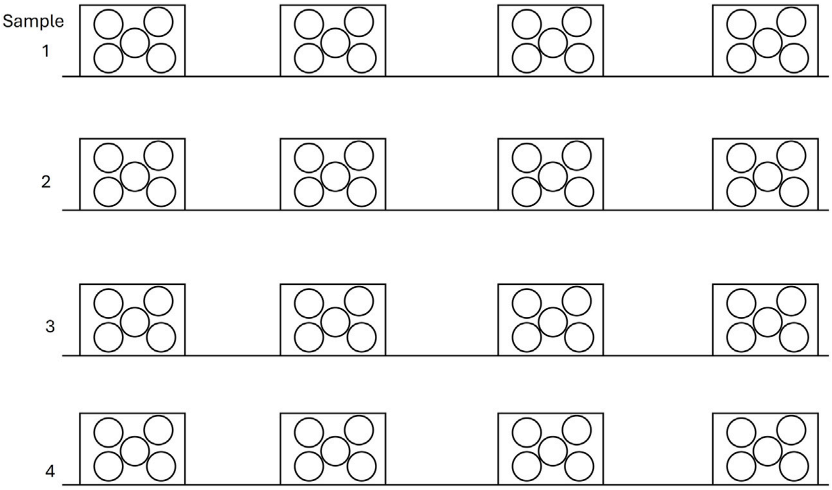

FIGURE 3 | Soil sampling scheme: Four transects were carried out in each area subjected to the different treatments studied: C, B, CL, from which four composite samples were collected. Each composite sample consisted of five surface soil measurements taken at a depth of 0–3 cm.

To perform soil sampling, in each plot, four representative and equidistant 30 × 30 cm surfaces were established along the four transects used for vegetation analysis. At each point, five surface soil samples (0–3 cm) were collected and combined to form a composite sample per point. Subsequently, the composite samples from the four points within each transect were further mixed, resulting in a four composite soil sample representative of each treatment (**Figure 3**). A similar sampling was repeated in unburned plots, collecting the soil samples next to shrubs. This sampling approach was based on prior observations indicating that the immediate effects of wildfires on soil properties are generally confined to the top few centimeters due to the high thermal inertia of soil (Alfaro-Leranoz et al., 2024; Pereira et al., 2023). All samples were collected in plastic bags to avoid desiccation and were rapidly transported and stored at 4°C to maintain the fresh conditions. In addition, two undisturbed surface cores were collected for each transect for bulk density determination. In **Figure 3**, the samples are represented within a square geometry reflecting the method used during collection. Litter was first removed from a

30 × 30 cm surface area and soil was subsequently extracted using soil coring cylinders.

Determination of Soil Properties

A fresh soil subsample was stored at 4°C for biological analyses. The rest of the soil samples were air-dried to constant weight and sieved to 2 mm for physical and chemical analysis. Additionally, a portion of the air-dried sample was ground into a fine powder.

Field capacity (FC) was determined using the method of Klute. (1986), permanent wilting point (PWP) with a pressure membrane equipment, aggregate stability (SAS) according to Kemper and Koch (1966) methodology, bulk density (BD) following the cylinder method of Blake and Hartge (1986), soil moisture was calculated gravimetrically until constant weight, and the persistence of soil water repellency was calculated with water drop penetration test (WDPT) proposed by Bisdom et al. (1993) using the classes of Doerr et al. (2000) on air-dried and 2-mm sieved soil.

The current pH was determined potentiometrically in a 1:2.5 (w/v) soil water mixture, and electrical conductivity (EC) was measured in a 1:5 (w/v) soil extract following Page et al. (1982) procedures.

Oxidizable organic carbon (OOC) was measured trough chromic oxidation (Page et al., 1982), total organic matter (TOM) was obtained by dry combustion (Heiri et al., 2001), dissolved organic matter (DOM) extracted with a soil/water suspension (1:5 w/v) at 80°C and measured trough wet oxidation method (Ghani et al., 2003), And recalcitrant organic matter (ROM) was determined through the acid hydrolysis (HCl 6N) procedure (Rovira and Ramón Vallejo, 2007). SOC mineralization was measured in an incubation assay (41 days) of soil samples under optimal temperature (25°C) and moisture (75% water-holding capacity) conditions. The released CO_2 was captured with soda traps (Anderson, 1983) and measured at 2-day intervals at the start of the assay. As respiration rates declined over time, the frequency of measurements was reduced accordingly. The measurement obtained was the weight of C-CO_2. The values of C-CO_2 emitted during incubation can be fitted to a simple first-order kinetic model, represented by the following formula: $C_t = C_0\,(1 - e^{-kt})$, where C_t refers to the accumulated amount of C-CO_2 (mg C kg soil^{-1}) emitted over time t, C_0 is the initial content of mineralizable carbon (mg C kg soil^{-1}), and k is a constant representing the daily flux rate (days^{-1}).

Biological Characterization

The potential enzymatic activity involved in different stages of soil organic carbon cycles were determined through β-D-glucosidase analysis by using the method of Eivazi and Tabatabai (1988). According to this method, soil samples were incubated with substrate (β-D-glucopyranoside) for 1 h at 37°C in a medium buffered at pH 5. Then, the product (p-nitrophenol) was extracted by filtration after adding $CaCl_2$ and tris (hydroxymethyl) aminomethane buffer at a pH of 12. Finally, the concentration of p-nitrophenol was determined by colorimetry based on the yellow colour in the solution.

Carbon source utilization patterns of sol microbial communities (CLPP) were determined with Biolog EcoPlates (BIOLOG INC, Hayward, CA) as described by Liang et al. (2016). A single Biolog™ EcoPlate was used for each soil sample, resulting in three replicates per sample. Each EcoPlate was inoculated with a 130 µL aliquot of a soil dilution prepared from 1:10 (Dw/v) suspensions of fresh soil in autoclaved 0.85% sodium chloride solution, containing 3 g of glass beads to facilitate physical dispersion of the sample. The suspension was shaken on an orbital shaker at 220 rpm for 30 min. Following shaking, the soil suspension was centrifuged at 2,600 rpm for 10 min. The supernatant was carefully decanted and centrifuged again at 2,600 rpm for an additional 10 min. A 2 mL aliquot of the resulting supernatant was then pipetted and transferred into 30 mL tubes containing 18 mL of autoclaved 0.85% sodium chloride solution. This process was repeated twice to achieve a 10^{-3} dilution. The development of color in the wells indicates the potential activity of the bacterial community on a specific substrate, i.e., the intensity of microbial carbon use, which is measured by the average well color development (AWCD) (Braun et al., 2010; Fontúrbel et al., 2016; García Lucas, 2013). The diversity of the microbial community is estimated based on the carbon sources used in the EcoPlates—amines, amino acids, carbohydrates, carboxylic acids, phenols, and polymers—was determined using species richness (SR) as the number of utilized substrates, the Shannon-Wiener index (H'), Pielou's evenness index (J'), and the average well color development (AWCD) at 96 h post incubation. Evenness represents the proportion of observed diversity in relation to the maximum expected diversity (Magurran, 2013).

Fungal activity was assessed by estimating total glomalin content (T-GRSP) and easily extractable glomalin (EE-GRSP) following the method of Wright and Upadhyaya (1996). Easily Extractable Glomalin (EEG) was used for tracing structural changes in SOM given by the vegetation cover and the occurrence of wildfires (San Emeterio et al., 2024).

Statistical Analysis

Despite being aware of the presence of pseudoreplicates — a common issue in studies examining the effects of wildfires — we acknowledge that obtaining proper replicates is challenging without introducing variability in the geomorphological and ecological characteristics of the samples, such as orientation, elevation, soil type, or moisture (Davies and Gray, 2015). To analyze the effect of management practices on soil functionality and activity, a one-way ANOVA was conducted.

Prior to the ANOVA, data normality and homoscedasticity were assessed. For non-normal data, a Box-Cox transformation was applied to meet the assumptions of the test. The significance level for the ANOVA was set at $p < 0.05$. In addition, a principal component analysis (PCA) was performed to identify the main associations within the measured data.

All statistical analyses were conducted using JASP version 0.19.0 for Windows (JASP Team, 2024) and PAST software (Hammer et al., 2001).

TABLE 1 | Effects of shrub clearing and burning on soil properties for a soil depth of 0–3 cm (n = 4). Means ± standard deviations are presented for each treatment, along with significance levels (p-values).

Treatments				
Property	**Burned**	**Cleared**	**Control**	**P-value**
pH	6.16 ± 0.51 a	6.24 ± 0.38 a	5.28 ± 0.30 b	0.016
EC (µs/cm)	174.06 ± 152.29 a	67.48 ± 14.39 b	444.63 ± 30.42 a	0.001
Moisture (g/kg)	65.74 ± 58.24 b	99.19 ± 25.24 b	314.13 ± 61.57 a	0.0001
BD (kg/m^3)	1,049.33 ± 66.66 b	1,098.94 ± 102.62 b	1,296.37 ± 54.96 a	0.012
SAS (%)	42.33 ± 11.05	54.49 ± 9.54	52.40 ± 3.78	0.163
FC (g/kg)	194.96 ± 41.02	217.51 ± 16.78	227.85 ± 27.60	0.333
PWP (g/kg)	103.22 ± 23.23	120.11 ± 24.26	129.72 ± 9.26	0.223
TOC (g/kg)	5.13 ± 10.16	6.74 ± 11.31	7.16 ± 8.88	0.103
OOC (g/kg)	47.33 ± 10.93	50.37 ± 7.95	53.49 ± 6.29	0.694
DOC (g/kg)	26.58 ± 5.07	27.71 ± 7.05	26.72 ± 2.31	0.946
ROC (g/kg)	22.42 ± 17.01	19.81 ± 3.58	27.36 ± 2.51	0.667
T-GRSP (g/kg)	2.70 ± 0.93	2.08 ± 0.44	2.49 ± 0.29	0.324
EE-GRSP (g/kg)	0.32 ± 0.09	0.38 ± 0.29	0.65 ± 0.12	0.693
GLU (µmoles PNP/g h)	8.15 ± 1.58 b	10.98 ± 0.35 b	11.96 ± 0.62 a	0.001

Different lowercase letters (a, b) indicate significant differences between treatments according to one-way ANOVA ($p < 0.05$).

Table legend: EC: electrical conductivity, BD: bulk density, SAS: aggregate stability, FC: field capacity, PWP: permanent wilting point, TOC: total organic carbon, OOC: oxidizable organic carbon, DOC: dissolved organic carbon, ROC: recalcitrant organic carbon, T-GRSP: total glomalin, EE-GRSP: easily extractable glomalin, GLU: β-D-glucosidase.

RESULTS AND DISCUSSION

Effect on Soil Physical and Chemical Properties

A significant difference (p = 0.016) has been found in the soil pH between the control soils (pH = 5.3 ± 0.30) in relation to those subjected to clearing (CL) and burning (B), in which the pH is 6.2 in both treatments. This acidic pH indicates that cation leaching tends to drive the soil toward oligotrophic conditions, reflecting a gradual loss of basic nutrients (**Table 1**).

All soil samples are hydrophilic (WDPT <5 s) with low electrical conductivity (EC values ranging from 444.63 ± 30.42 to 67.48 ± 14.39 µS/cm), showing significant differences between the control and the cleared and burned samples (p = 0.006) (**Table 1**). The soils exhibit moderate aggregate stability (SAS 42.33% ± 11.05% to 54.49% ± 9.54%) and contain abundant oxidizable organic carbon (OOC from 47.33 ± 10.93 to 53.49 ± 6.29 g/kg) with no significant differences observed among treatments (**Table 1**).

Some studies suggest that significant reductions in soil carbon may only become evident in the long-term following fire events (Girona-García et al., 2019; Girona-García et al., 2018). Additionally, any potential initial carbon loss may be offset by organic inputs from decomposing subterranean roots and the incorporation of charcoal produced during the fire. These factors act as indirect effects of fire, influencing the soil both in the short and long term. However, the impact of fire on soil organic matter remains uncertain, as it depends on the intensity and frequency of fires, the type of vegetation present and its associated fuel load, as well as the physical and chemical properties of the soil (Knicker, 2007; Hobley et al., 2017; Alcañiz et al., 2018).

Overall, the general differences between treatment groups were not pronounced. This could be attributed to the fact that the differences were subtle and did not affect the soil globally. Soil quality was primarily influenced by its long-term management history, which affected its structure, organic matter content, and biodiversity. Recent and isolated disturbances, such as fire and mechanical clearing, caused immediate changes, but their impact was often less significant than the cumulative effects of historical management practices (Blanco and Lal, 2008), suggesting that the observed differences might not be exclusively attributable to the treatments.

Effect on Soil Biological Properties

Differences in β-D-glucosidase, that represented the enzymatic activity, have been found between management treatments, specifically the burned and cleared soils present a significantly (p = 0.001) lower value than the control soil (**Table 1**). The activity was 8.15 ± 1.58 µmol PNP/g h for the burn treatment, 10.98 ± 0.35 µmol PNP/g h for the clearing treatment, and 11.96 ± 0.62 µmol PNP/g h for the control.

Some studies establish a direct influence of fire, as the high temperatures reached during fires can lead to the denaturation and deactivation of enzymes associated with soil colloids (Armas-Herrera et al., 2016; Lombao et al., 2021). However, 6 months post-fire, the activity of these enzymes rapidly recovers (Girona-García et al., 2019), as variations are transient. Although seasonality may affect enzyme activity, differences typically disappear within a year after treatment. Therefore, reduced activity could be attributed to the indirect effects of fire caused by changes in the soil's physicochemical properties.

Although no significant differences were observed between the cleared and burned samples, the higher mean value observed in the cleared plot could be attributed to the transformation of surface organic residues, as these residues had nearly disappeared from the surface of the plots 2 years after treatment. Conversely, studies conducted in the central Pyrenees have not observed significant effects of fire on enzymatic activity or any modification due to the introduction of livestock (San Emeterio et al., 2016). Therefore, it is important to consider the possibility that differences observed in β-D-glucosidase activity could be

TABLE 2 | Diversity in carbon sources consumed from Ecoplates, Species Richness, Shannon-Wiener index, Pielou's evenness index, and Average Well Color Development (AWCD) at 96 h of incubation (n = 10). Means ± standard deviations are presented for each treatment, along with significance levels (p-values).

	Burned	Cleared	Control	P-value
Species Richness	16.83 ± 7.28	21.08 ± 1.81	17.71 ± 2.73	0.423
Shannon-Wiener index, H′	2.77 ± 0.45	3.01 ± 0.10	2.78 ± 0.17	0.440
Pielou's evenness index, J′	1.00 ± 0.00	1.00 ± 0.01	0.98 ± 0.04	0.484
AWCD (OD_{595})	0.12 ± 0.07	0.19 ± 0.08	0.27 ± 0.07	0.359

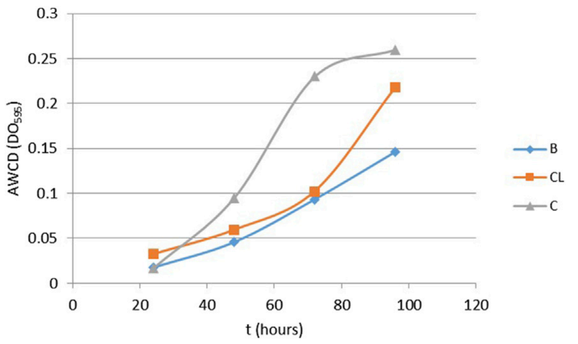

FIGURE 4 | Average well color development (AWCD), over 96 h, using Biolog Ecoplates in burned (B), cleared (CL) and control (C) soils.

influenced not only by the treatments applied but also by pre-existing natural differences between the study sites. This aspect may relate to pseudoreplication in the experimental design, as the sites selected for each treatment could have differed in their initial characteristics, such as nutrient availability or the microbiota present, potentially affecting the results independently of the treatments. Thus, while the results suggest an effect of the burning and clearing treatments, initial differences between the sites should be considered as a potential source of variability in the observed enzymatic activity.

Although fungal activity, measured through total glomalin-related soil protein (T-GRSP) and easily extractable glomalin-related soil protein (EE-GRSP), did not show significant differences in either fraction (p = 0.324 and p = 0.693, respectively), certain trends were observed in the obtained values. The average T-GRSP in the burned treatment was higher (2.70 ± 0.93 g/kg) compared to the other treatments, a common outcome following burning, though these values tend to decrease over time (Alfaro-Leranoz et al., 2022). Regarding EE-GRSP, no statistically significant differences were observed among treatments, suggesting that fungal activity was not damaged, as this fraction of glomalin represents the most recently formed portion. San Emeterio et al. (2024) considered EE-GRSP to be structurally homogeneous and likely resistant to temperatures below 200°C–250°C. Consequently, the occurrence of fires and even the type of vegetation cover can significantly influence the molecular structure of EE-GRSP. Additionally, due to mineralization, EE-GRSP eventually becomes recalcitrant, a process of significant importance since glomalin can have a soil residence time ranging from 6 to 42 years, depending on soil type and conditions (Wright and Upadhyaya, 1996; Rillig et al., 2001).

However, the lower mean value for EE-GRSP observed in the burned plot may be attributed to the impact of fire on arbuscular mycorrhizal fungi, resulting in a reduction in the number of propagules. This could potentially reduce the soil's capacity to transform organic matter in the future (Pietikäinen and Fritze, 1995; Mataix-Solera et al., 2009). This reduction is also reflected in the inverse relationship between total glomalin and β-D-glucosidase activity, as illustrated in **Figure 7**. Nonetheless, it is plausible that these differences were partially influenced by the initial conditions of the sites prior to burning. Glomalin levels are linked to mycorrhizal fungal activity, which can vary naturally among sites, highlighting the possibility that the observed differences were not solely due to treatment effects but also to initial disparities associated with pseudoreplication.

The potential functional diversity of the soil microbial community was evaluated using a community-level physiological profile (CLPP) approach (García Lucas, 2013). The average color development (AWCD-DO_{595}) values, which ranged between 0.27 ± 0.07 and 0.12 ± 0.07, (**Table 2**; **Figure 4**), did not exhibit statistically significant differences ($p = 0.359$). The highest average value was observed in the control sample (0.27 ± 0.07 DO_{595}), followed by the cleared (0.19 ± 0.08 DO_{595}) and burned (0.12 ± 0.07 DO_{595}) samples. However, the cleared and burned samples had not yet stabilized after 96 h of incubation, suggesting that the microbial communities in the control plot had a higher and faster AWCD kinetic, while those in the burned and cleared plots were slower.

The carbon sources utilized by the microbial community showed a noticeable difference between the control sample and those subjected to clearing or burning (**Figure 5**). In the cleared plot, greater utilization of amino acids (0.77 ± 0.66 DO_{595}), carbohydrates (0.619 ± 0.55 DO_{595}), and carboxylic acids (0.57 ± 0.42 DO_{595}) was observed. In contrast, in the burned plot, amino acids (0.60 ± 0.67 DO_{595}) were the most utilized sources. This suggests that the microbial community in the cleared and burned plots had a higher affinity for consuming simple carbon and nitrogen sources, potentially indicating the presence of simpler organic matter forms in these soils (Koner et al., 2021). Control samples exhibited lower overall carbon source utilization but showed a preference for more complex carbon sources, such as polymers and phenolic compounds, albeit only slightly higher than in the burned and cleared samples. Amines were also utilized by the control microbial community,

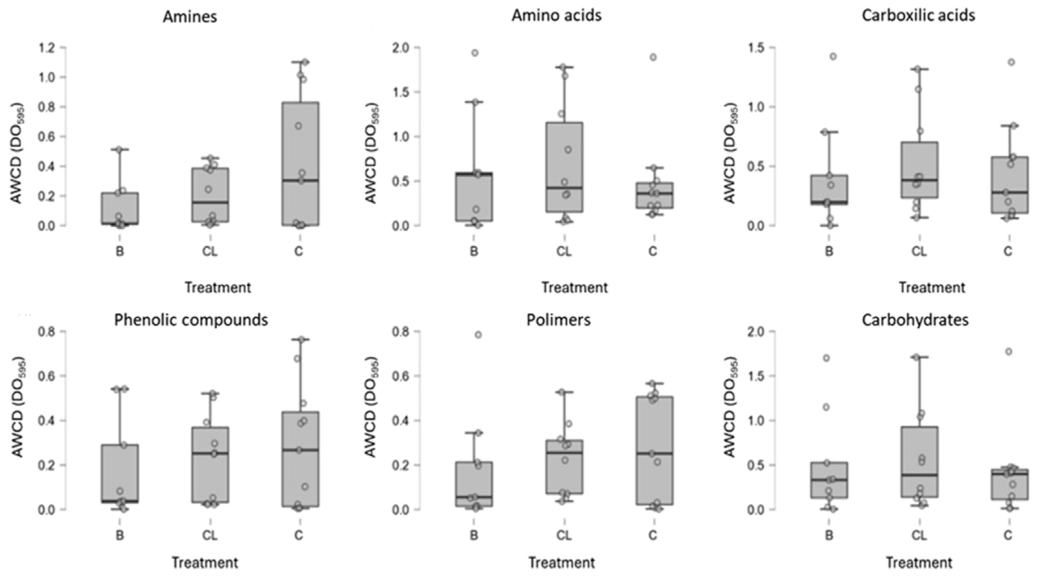

FIGURE 5 | Catabolic activity (AWCD) of the bacterial community based on substrate families consumed and the management system (n = 9).

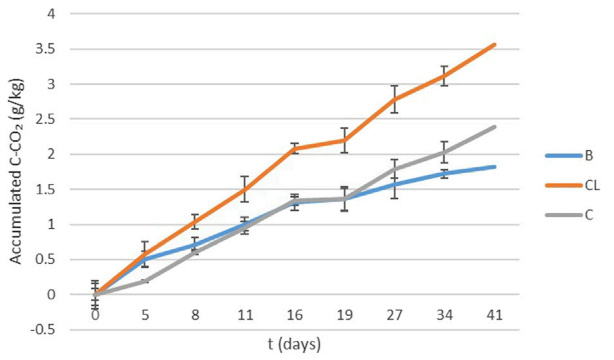

FIGURE 6 | Soil respiration expressed as cumulative C-CO$_2$ emitted during the incubation assays (41 days) in burned (B), cleared (CL) and control samples (C).

suggesting that the bacterial community in these plots retained the ability to degrade complex carbon sources and actively participated in the nitrogen cycle by breaking down amine-containing compounds. Bacteria capable of degrading amines can convert them into compounds such as ammonia or nitrates, potentially contributing to the mineralization of nitrogenous organic compounds and aiding in nutrient recycling.

These findings highlight the resilience of microbial communities, recovering over the short term, reaffirming previous observations that microbial activity and carbon source utilization abilities recover approximately 6 months after fire (Lombao et al., 2020). Although no significant differences were observed between the burned and cleared samples (**Table 2**), the higher mean microbial activity values after clearing could be attributed to the positive effects of residual vegetation cover and the incorporation of plant residues into the soil. Additionally, microbial responses in plots subjected to prescribed burns are influenced by the fire's severity and subsequent vegetation recovery. However, this effect may be transient, with activity levels potentially returning to their original state 4–6 years post-disturbance (Huhta, 1976). Herbivores also influence the plant-soil system through their impacts on plant composition and microbial communities. This interaction could explain why the burned and cleared plots exhibited greater carbon source utilization, as grazing occurred in these two plots (Debouk et al., 2020).

It is worth noting that the impact of each management method might be underestimated when using the CLPP technique, as microbial families exhibit functional redundancy, allowing different microbial communities to utilize the same carbon sources (Staddon et al., 1997). For this reason, it is essential to complement CLPP with an ecological diversity index analysis of carbon source utilization (**Table 2**). Moreover, since the carbon sources consumed depend on numerous factors, including the quantity and quality of available organic matter, it is crucial to consider that differences in carbon source utilization might result from the initial characteristics of the sites, such as the original composition of microbial communities, rather than solely from management effects.

A significant positive correlation was observed between amines and total organic carbon ($r = 0.646$, $p = 0.021$), suggesting that although total organic matter is abundant, nitrogen in readily available forms (such as ammonia or nitrates) may be limited, prompting microorganisms to utilize amines as an alternative nitrogen source. Alternatively, it could indicate that the TOM is particularly rich in nitrogen. In this case, a higher nitrogen-rich TOM could facilitate microbial access to amides as a nutrient source. Therefore, the positive relationship

TABLE 3 | k constant values of the single-compartment model and average residence time (ART) of the organic matter for basal soil respiration in burned, cleared, and control samples (n = 4). Means ± standard deviations are presented for each treatment, along with significance levels (p-values).

	Treatments			P-value
	Burned	Cleared	Control	
Constant k (days^{-1})	4.25 ± 1.9 × 10^{-4} b	8.25 ± 1.7 × 10^{-4} a	5.25 ± 5 × 10^{-4} b	0.011
1/K MRT (years)	7.25 ± 2.48 a	3.44 ± 0.80 b	5.25 ± 0.46 b	0.020

Different lowercase letters (a, b) indicate significant differences between treatments according to one-way ANOVA (p < 0.05).

suggests that microorganisms are taking advantage of nitrogen-containing compounds present in the TOM, indicating a nitrogen-rich environment. This scenario is plausible in burned samples, as fires often result in increased nitrogen availability immediately following the event (Canals et al., 2024).

In the potential microbial catabolic activity richness and substrate utilization diversity (**Table 2**), a trend toward utilizing a greater number of carbon substrates was observed in the cleared plots compared to the others, although this difference was not statistically significant (p = 0.423). Notably, the data exhibited a lower degree of dispersion, indicating a higher level of homogeneity in substrate utilization. This suggests that bacterial communities under this condition displayed more consistent and uniform metabolic behavior. Such functional homogeneity may reflect better microbial community adaptation to environmental conditions or more efficient and uniform access to available carbon sources, underscoring the role of environmental stability or resource distribution.

Although statistically significant differences among treatments were absent, the higher mean values in cleared samples may reflect the positive impact of applying cleared material as biodegradable mulch. This practice likely enhances soil microbiota and influences soil physical and chemical properties, such as increasing water retention, maintaining appropriate soil temperatures, and improving nutrient dynamics (Aslam and Haider, 2022).

In the richness of consumed substrates, no statistically significant differences were observed. However, significantly greater heterogeneity was found in samples from plots subjected to prescribed burns, with a value of 16.83 ± 7.28. This heterogeneity could be attributed to increased nitrogen availability following fires, which can lead to short-term increases in biological productivity, as observed in the sampling conducted by Hamman et al. (2008). These findings suggest that burning impacts microbial behavior despite the treatment having occurred 2 years prior. Fire's direct effects can persist, altering microbial biodiversity, creating or destroying niches, and affecting plant biomass and species (Mataix-Solera et al., 2009).

The same applies to diversity as represented by the Shannon index, where no significant differences (p = 0.440) were found among the treatments, with values ranging from 2.77 to 3.01. This response is consistent with other studies (Pineda and Lizarazo-Forero, 2013; Garnica and Solorio, 1995), which show that microorganisms are highly sensitive to changes in temperature, moisture, and nutrients resulting from shifts in plant cover, as often occurs after a fire. Even low-temperature fires can restrict microbial viability, and the direct and immediate effects of prescribed burns can significantly impact bacterial survival (Moya et al., 2022; Fontúrbel et al., 2024).

Mechanical clearing, while not directly altering the soil, changes environmental conditions for microbial communities, affecting their viability (Rutgers et al., 2016; Torres and Cabrera, 2005; Frazer et al., 1990). Existing differences may be more related to residues left by these treatments and changes in cover (**Table 4**). The presence of bare soil in burned and cleared plots can lead to greater water and wind erosion, increased evaporation and temperature, and altered nutrient cycling. These changes influence microbial communities by disrupting microbial balance and carbon source utilization during cellular growth, affecting the AWCD kinetics observed in **Figure 4**.

Figure 6 illustrates soil respiration as cumulative C-CO_2 emitted during the 41-day incubation assay for cleared, burned, and control soil samples. Cleared samples exhibited the highest percentage of accumulated C-CO_2 (3.56 ± 0.14 g/kg), suggesting greater microbial activity and/or higher organic matter content susceptible to decomposition compared to control (2.39 ± 0.15 g/kg) and prescribed burn (1.83 ± 0.06 g/kg) samples. Initially, all three treatments followed similar trajectories, indicating no pronounced differences in microbial activity or organic matter content. However, after the initial period, cleared samples showed a markedly higher rate of CO_2 accumulation.

In burn treatments, it has been observed that the greater the fire impact, the more carbon accumulates in refractory forms, leading to a greater loss of the more labile forms of carbon. This causes the baseline respiration levels to be lower in burned soils compared to unburned ones as it was observed previously in the work of Armas-Herrera et al. (2016), who evaluated the immediate effects of prescribed burning in the Central Pyrenees on the quantity and stability of organic matter in the top few centimeters of the soil. This trend is also reflected in the values of the constant k and in the values of the mean residence time (MRT) of organic matter. As shown in **Table 3**, significant differences were found between treatments for the constant k (p = 0.011) and the MRT (p = 0.020).

The burned sample exhibited a higher mean residence time (MRT) of organic matter (7.25 ± 2.48 years) and a lower decomposition rate constant (k = 4.25 ± 1.9 × 10^{-4} days^{-1}), indicating that organic matter remained in the soil for a longer period, reflecting greater recalcitrance. This suggests that organisms require more time to degrade organic matter in burned plots. A higher amount of recalcitrant organic residue (MOR) points to a shift in the quality of soil organic matter (SOM). Burning alters the composition of organic matter by

TABLE 4 | The percentage of vegetation covers 2 years after interventions in the burned and cleared plots (n = 4). Means ± standard deviations are presented for each treatment, along with significance levels (p-values).

	Treatments			P-value
	Burned	**Cleared**	**Control**	
Gramineae (%)	26.12 ± 14.09 b	32.87 ± 3.68 a	12.24 ± 2.57 b	0.005
Leguminosae (%)	1.98 ± 2.83	5.44 ± 5.99	0.00 ± 0.00	0.182
% *Echinospartum horridum* (%)	12.94 ± 5.39 b	16.64 ± 4.54 b	73.69 ± 3.36 a	0.0002
% Other species (%)	22.90 ± 13.34	17.17 ± 17.64	14.07 ± 4.16	0.240
% Bare soil (%)	16.85 ± 6.87 a	5.89 ± 4.26 a	0.00 ± 0.00 b	0.002
% Leaf litter (%)	19.21 ± 7.74 b	21.99 ± 12.06 a	0.00 ± 0.00 b	0.009

Different lowercase letters (a, b) indicate significant differences between treatments according to one-way ANOVA (p < 0.05).

increasing the proportion of recalcitrant structures, leading to a higher proportion of recalcitrant organic carbon (ROC) in the burned samples compared to the cleared plot. Microbial activity, as measured by parameters such as AWCD (Average Well Color Development), glucosidase activity, and respirometry, was lower in the burned samples. However, these differences could be related not only to the direct effect of the burning treatment but also to initial variations in the quality of organic matter or the physicochemical characteristics of the studied soils. The influence of pseudoreplication may also be a factor, limiting the ability to attribute these differences exclusively to the applied treatment. In contrast, cleared samples demonstrated higher microbial activity, as evidenced by the AWCD value, and a lower MRT of organic matter (3.44 ± 0.80 years). The control plot, with an MRT of 5.25 ± 0.45 years, showed a trend like the cleared plot.

Evolution of Vegetation Cover

Two years after the treatments, aerial biomass reached 9.88 ± 4.61 Mg/ha in the burned plot and 19.24 ± 7.22 Mg/ha in the cleared plot (p = 0.072). The presence of mulching increases soil temperature and moisture, which translates to greater microbial and enzymatic activity, as observed in **Table 1**. In contrast, drier sites, such as the burned plot, inhibit these positive effects. Soil enzymatic activities are indicators of soil organic matter quality, and vegetation significantly influences enzymatic activity by regulating the quality of microbial biomass (Sardans et al., 2008; Debouk et al., 2020).

The shrub removal treatment altered the composition of vegetation functional groups (**Table 4**). Two years after the clearing and burning treatments, *E. horridum* has a similar cover of 16.64% ± 4.54%, and 12.94% ± 5.39% respectively, which are significantly (p = 0.0002) lower than the control plot, with 73.69% ± 3.36%. Despite the higher percentage of *E. horridum* in the burned plot compared to the control plot, the results suggest that both treatments were effective in reducing shrub dominance and improving the biodiversity of the resulting pastures. The covers data obtained are very similar to those previously inventoried in other areas of the central southern Pyrenees (Mora et al., 2022).

Although *E. horridum* is a legume, it was excluded from the legume functional group for quantification purposes, as the primary objective of the applied control measures was to manage its growth and establishment. *Echinospartum horridum* is a fire-adapted leguminous shrub that benefits from prescribed burning, as fire promotes its reproductive potential by stimulating seed bank germination. This process facilitates the establishment and recovery of the species, which can achieve full vitality and soil cover approximately 4–5 years after a fire (Mora et al., 2022; Alados et al., 2019). Since the sampling was conducted 2 years after the intervention, it is premature to assess the final state of shrub cover. However, coverage in the burned plot is expected to increase relative to the cleared plot over time. This behavior has also been observed in wetter regions of the Pyrenees, where issues of shrub encroachment are driven by *Ulex gallii*, another woody legume that exhibits reproductive advantages, enabling it to become invasive or dominant over other species (Múgica et al., 2024), like *E. horridum*.

In both treatments, grasses were the dominant functional group, with a higher coverage percentage in the cleared plot (33% ± 3.68%) compared to the burned plot (26% ± 14.09%). Significant differences (p = 0.005) were observed between the cleared plot and the control and burned plots, which did not show significant differences between each other. Although legumes were not particularly abundant in any of the plots, they were more prominent in the cleared treatment (5.44% ± 5.99%). No significant differences (p = 0.182) were observed. This functional group plays a crucial role as nitrogen fixers in the soil (Simón et al., 2005). Cleared plots exhibit a significantly higher percentage of Gramineae cover compared to both burned and control plots. These results suggest that the different treatments have distinct effects on this functional group, with clearing potentially promoting their growth more than burning or leaving the plot undisturbed. This is particularly important in mountain pastures, such as the study area, because grasses provide significant biomass, serve as a high-calorie, protein-rich food source for animals, and their extensive root systems prevent soil compaction and establish quickly, thereby reducing erosion risks (Martínez Romero and Leyva Galán, 2014).

A significant difference in bare soil was also observed (p = 0.002), with a higher percentage in the burned plot (17% ± 6.87%) compared to the cleared plot (5.89% ± 4.26%). The loss of natural cover is one of the most critical factors affecting soil fertility and natural productivity, as it leaves the soil vulnerable to various erosive agents (Muñoz-Iniestra et al., 2009).

Multivariable Analysis

The principal component analysis (PCA) of the physical, chemical, and biological properties of the analyzed soils

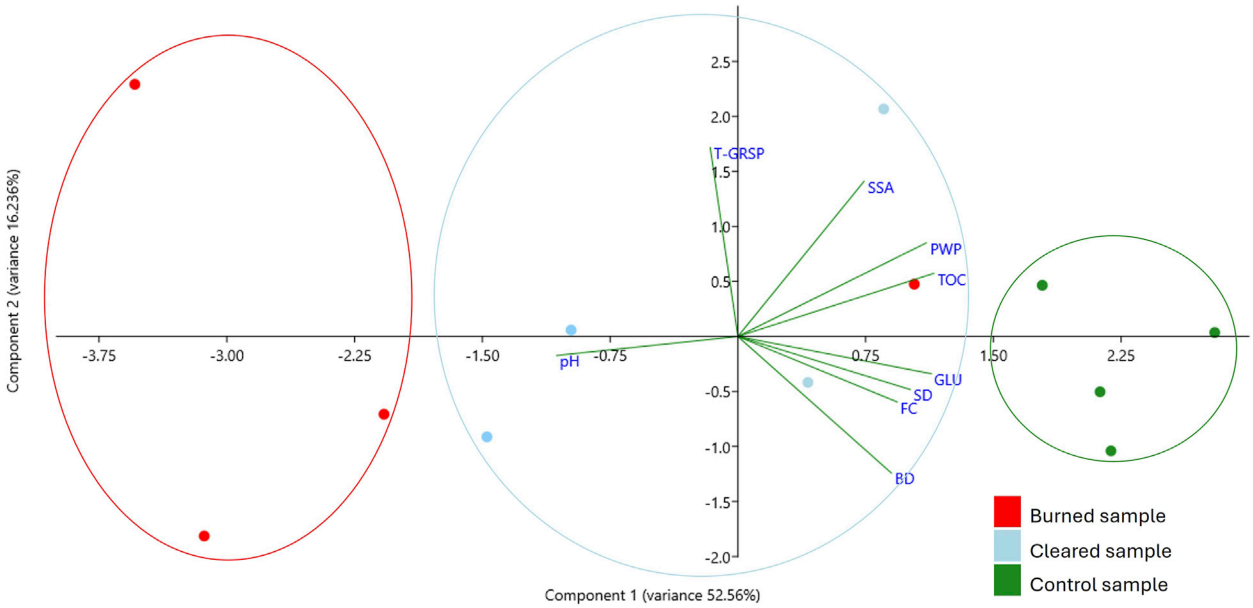

FIGURE 7 | PCA of burned, cleared, and control samples, with principal component 1 explaining 52.56% of the variance and principal component 2 explaining 16.24%.

(**Figure 7**) revealed that the main differences were due to fertility characteristics and biological activity. The first component (PC1) explained 52.56% of the variance, while the second component (PC2) explained 16.23%. This analysis was conducted to reduce data dimensionality and uncover underlying patterns in the variables influencing soil properties.

Control samples cluster in the positive region of Component 1 and the negative region of Component 2. This suggests that variables with strong positive loadings in Component 1, such as TOC (0.40) and GLU (0.39), are characteristic of these samples. On the other hand, variables with weaker contributions, such as pH (−0.37), show an inverse relationship with the positive loadings of this component.

Burned samples tend to occupy the negative quadrants of both components, reflecting a distinct pattern influenced by variables like BD and FC, which are moderately correlated with Component 1 (0.31 and 0.32, respectively). Cleared samples are more scattered, but they tend to align with the positive region of Component 2, influenced by variables such as T-GRSP (0.59) and SAS (0.49), which show strong positive loadings on this axis.

The relationship between variables and components highlights divergence. For example, T-GRSP shows a strong association with Component 2 but a near-zero contribution to Component 1, indicating its specific influence on certain samples. In contrast, variables like PWP and TOC contribute positively to both components, indicating a broader relationship with multiple sample types. These patterns suggest that variables positively associated with Component 1, such as TOC and GLU, are key markers for control samples, while those strongly associated with Component 2, like T-GRSP, may characterize cleared samples. Burned samples reflect unique associations with negative loadings, which may indicate altered soil properties or organic matter degradation in these samples.

The PCA determines that for the cleared and burned samples, T-GRSP and SAS in Component 2 carry greater weight, whereas for control samples, TOC and GLU in Component 1 are more influential.

Combining the results from the biological properties section with the PCA, it is observed that cleared soils exhibit higher microbial activity, which could be related to the increased presence of DOC and GLU (Debouk et al., 2020). Dissolved organic carbon is a readily accessible carbon source for soil microorganisms, serving as both an energy and nutrient source. Microorganisms use this carbon as a primary energy source, accelerating the decomposition of soil organic matter, increasing mineralization rates, and enhancing microbial respiration (Fierer and Schimel, 2002; Kalbitz et al., 2000). GLU catalyzes the hydrolysis of glycosidic bonds in complex carbohydrates, breaking them down into simple sugars that microorganisms can use as energy sources (Allison and Vitousek, 2005; Bell et al., 2008; Sinsabaugh et al., 2008).

The substantial impact of burning on soil bacteria is often emphasized, which might seem contradictory to the results obtained. This discrepancy can be explained by changes in the proportion of oxidizable organic carbon caused by fire compared to total organic carbon. When the ratio (OOC/TOC) is calculated, the burned plot has the highest proportion (OOC/TOC = 5.18), compared to the cleared and control plots, which have values of 4.11 and 3.73, respectively. This suggests that, although the lower species richness in the burned plot (**Table 2**), the increased availability of DOC may result in higher biological activity at the onset of post-fire recovery, compensating for the lower number of microorganisms. However, this initial increase in microbial activity may eventually be followed by the depletion of remaining carbon and nitrogen forms (Mataix-Solera et al., 2009).

On the other hand, the greater weight of SAS for both treatments may be due to its indirect alteration by fire, as heat released during the fire can directly affect aggregation. This in turn can have indirect effects on vegetation recovery, soil erosion, and degradation (Mataix-Solera et al., 2011). However, in both cases, much of this effect can be attributed to the indirect impacts of the treatments, driven by different vegetative covers. Many studies have shown that several direct effects fade over the short to medium term, leaving primarily indirect effects (Girona-García et al., 2018). A similar case applies to glomalins, where changes in vegetation cover types affect microbial communities (Lozano, 2015).

The heterogeneity of the samples in the burned and cleared plots must be considered when interpreting the results, as it introduces significant variability and high deviations in some determinations. Two subsamples from both treatments shared common soil properties and behaved similarly to the control samples, as shown in **Figure 7**. This may be due to variations in the shrub control methods applied, such as fire intensity, once again highlighting the importance of the temperatures reached or the amount of vegetation cleared. This heterogeneity is reflected in the total and dissolved organic matter values of these two points, with the burned and cleared plots showing 38.77% and 28.88% more dissolved organic carbon (DOC), and 50.59% and 31.45% more total organic carbon (TOC), respectively, compared to other subsamples.

It is also important to consider the spatial proximity of the plots, which may further explain this heterogeneity. The burned and control plots are adjacent to one another (**Figure 2**), while the cleared plot is located 0.38 km away. Notably, the two subsamples mentioned earlier are the closest to the transition between plots, which may have influenced their soil properties. Therefore, it is crucial to recognize that the observed differences could be influenced by specific initial conditions of the sites selected for each treatment. Consequently, the results should be interpreted considering both the effects of the treatments and the pre-existing natural characteristics of the sites, which may be modulating the observed responses.

CONCLUSION

Two years after the management treatments were implemented, both methods were effective in controlling the spread of *E. horridum*, reducing the presence of monospecific slopes dominated by this species, and promoting the recovery of the original vegetation, fostering grasslands with greater vegetation diversity. However, there were statistically significant differences in the vegetation cover percentages obtained, with the burned plot behaving similarly to the control plot in terms of the percentage of grasses, legumes, and litter. Although both treatments achieved greater plant diversity, this diversity was higher in the cleared plot. For a better evaluation of this diversity, incorporating the control of the target plant community would have been necessary.

Significant differences were found in the soil parameters studied, indicating that soils were primarily affected indirectly by changes in vegetation cover resulting from the implementation of both treatments. More pronounced differences were observed in some physical and chemical properties, such as pH, electrical conductivity, moisture, and bulk density. However, these remained within optimal ranges for the soil and consistently exhibited similar behavior in cleared and burned samples compared to control samples. Biological properties showed the fewest statistically significant differences, with variations observed only in β-D-glucosidase activity and in the k constant values of the single-compartment model and the average residence time of organic matter for basal soil respiration. Nevertheless, the average values obtained suggest that the mechanical treatment or clearing practice yielded the best results 2 years after implementation. This can be attributed to the fact that biological properties are more significantly impacted by burning, as fire affects organisms both directly and indirectly through exposure to flames, gases, or other heat-transferring environments, as well as through changes in soil cover during the disturbance period. Additionally, soil microorganisms are particularly sensitive to environmental changes (Verma and Jayakumar, 2012; Hart et al., 2005).

Therefore, the initial hypothesis is rejected, as statistically significant differences were observed in the physical, chemical, and biological properties of the soil 2 years after the treatments were applied. However, the expected outcome regarding vegetation cover was confirmed, as the burned plot exhibited a lower percentage of *E. horridum*.

However, it is crucial to recognize that the observed differences in soil and vegetation responses could be partially due to the site's initial variability or inherent differences in environmental conditions, which may have introduced a degree of pseudoreplication in the experimental design. This variability highlights the importance of cautious interpretation of the results, as separating the effects of the treatment from the pre-existing site conditions may not always be straightforward.

Finally, it is essential to consider the land management history of these soils, the variability in how the treatments were applied, and the environmental heterogeneity of the study area, as these factors play an important role in the potential effects of control methods on soil properties. For future studies, it is crucial to conduct short-, medium-, and long-term monitoring of soil properties and vegetation cover to accurately determine the final effects of the different control methods, as well as to consider designs that minimize pseudoreplication to validate these findings.

DATA AVAILABILITY STATEMENT

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

AUTHOR CONTRIBUTIONS

SQ-E and DB-V performed the field sampling; SQ-E conducted the experiments; SQ-E, DB-V, and CM-D wrote the manuscript; SQ-E and CM-D performed the statistical analysis. All authors contributed to the article and approved the submitted version.

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CONFLICT OF INTEREST

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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REFERENCES

Agbeshie, A. A., Abugre, S., Atta-Darkwa, T., and Awuah, R. (2022). A Review of the Effects of Forest Fire on Soil Properties. *J. For. Res.* 33 (5), 1419–1441. doi:10.1007/s11676-022-01475-4

Alados, C. L., Saiz, H., Nuche, P., Gartzia, M., Komac, B., Frutos, D. E., et al. (2019). Clearing vs. Burning for Restoring Pyrenean Grasslands after Shrub Encroachment. *Geogr. Res. Lett.* 45 (2), 441–468. doi:10.18172/cig.3589

Alcañiz, M., Outeiro, L., Francos, M., and Úbeda, X. (2018). Effects of Prescribed Fires on Soil Properties: A Review. *Sci. Total Environ.* 613, 944–957. doi:10.1016/j.scitotenv.2017.09.144

Alfaro-Leranoz, A., Badia-Villas, D., Marti-Dalmau, C., Emran, M., Conte-Dominguez, A. P., and Ortiz-Perpiña, O. (2023). Long-term Evolution of Shrub Prescribed Burning Effects on Topsoil Organic Matter and Biological Activity in the Central Pyrenees (NE-Spain). *Sci. Total Environ.* 888, 163994. doi:10.1016/j.scitotenv.2023.163994

Alfaro-Leranoz, A., Badía-Villas, D., Martí-Dalmau, C., Escuer-Arregui, M., and Quintana.Esteras, S. (2024). The Effects of Fire Intensity on the Biochemical Properties of a Soil under Scrub in the Pyrenean Subalpine Stage. *Fire* 7, 452. doi:10.3390/fire7120452

Alfaro-Leranoz, A., Emran, M., and Badía-Villas, D. (2022). Glomalin-related soil protein evolution after prescribed burning of scrub in mountain soils (Central Pyrenees, NE-Spain). *Rev. Ciencias Agrar.* 45 (4), 477–481. doi:10.19084/rca.28572

Allison, S. D., and Vitousek, P. M. (2005). Responses of Extracellular Enzymes to Simple and Complex Nutrient Inputs. *Soil Biol. Biochem.* 37 (5), 937–944. doi:10.1016/j.soilbio.2004.09.014

Amsten, K., Cromsigt, J. P., Kuijper, D. P., Loberg, J. M., Jung, J., Strömgren, M., et al. (2024). Pyric Herbivory in a Temperate European Wood-pasture System. *J. Appl. Ecol.* 61 (5), 1081–1094. doi:10.1111/1365-2664.14618

Anderson, J. P. (1983). Soil Respiration. *Methods soil analysis part 2 Chem. Microbiol. Prop.* 9, 831–871. doi:10.2134/agronmonogr9.2.2ed.c41

Armas-Herrera, C. M., Martí, C., Badía, D., Ortiz-Perpiñá, O., Girona-García, A., and Porta, J. (2016). Immediate Effects of Prescribed Burning in the Central Pyrenees on the Amount and Stability of Topsoil Organic Matter. *Catena* 147, 238–244. doi:10.1016/j.catena.2016.07.016

Aslam, A., and Haider, F. U. (2022). "Effects of Mulching on Soil Biota and Biological Indicators of Soil Quality," in *Mulching in Agroecosystems: Plants, Soil and Environment* (Singapore: Springer Nature Singapore), 15–40.

Bell, C., McIntyre, N., Cox, S., Tissue, D., and Zak, J. (2008). Soil Microbial Responses to Temporal Variations of Moisture and Temperature in a Chihuahuan Desert Grassland. *Microb. Ecol.* 56 (1), 153–167. doi:10.1007/s00248-007-9333-z

Berninger, F., Susiluoto, S., Gianelle, D., and Balzarolo, M. (2015). Management and Site Effects on Carbon Balances of European Mountain Meadows and Rangelands. *Boreal Environ. Res.* 20 (6), 748–760.

Bisdom, E. B. A., Dekker, L. W., and Schoute, J. F. T. (1993). Water Repellency of Sieve Fractions from Sandy Soils and Relationships with Organic Material and Soil Structure. *Geoderma* 56, 105–118. doi:10.1016/0016-7061(93)90103-R

Blake, G. R., and Hartge, K. H. (1986). "Methods of Soil Analysis. Part 1," in *Physical and Mineralogical Methods*. 2nd Edn. (Madison, Wisconsin: A.S.A. – S.S.S.A).

Blanco, H., and Lal, R. (2008). *Principles of Soil Conservation and Management*, 167169. New York: Springer.

Bodí, M. B., Martin, D. A., Balfour, V. N., Santín, C., Doerr, S. H., Pereira, P., et al. (2014). Wildland Fire Ash: Production, Composition and Eco-Hydro-Geomorphic Effects. *Earth-Science Rev.* 130, 103–127. doi:10.1016/j.earscirev.2013.12.007

Braun, S., Thomas, V. F. D., Quiring, R., and Flückiger, W. (2010). Does Nitrogen Deposition Increase Forest Production? The Role of Phosphorus. *Environ. Pollut.* 158 (6), 2043–2052. doi:10.1016/j.envpol.2009.11.030

Canals, R. M., Múgica, L., Durán, M., and San Emeterio, L. (2024). Restorative Pyric Herbivory Practices in Shrub-Encroached Grasslands Enhance Nutrient Resource Availability And Spatial Heterogeneity. *Agric. Ecosyst. Environ.*, 109072. doi:10.1016/j.agee.2024.109072

Castillo-Garcia, M., Alados, C. L., Ramos, J., and Pueyo, Y. (2024). Effectiveness of Two Mechanical Shrub Removal Treatments for Restoring Sub-alpine Grasslands Colonized by Re-sprouting Woody Vegetation. *J. Environ. Manag.* 349, 119450. doi:10.1016/j.jenvman.2023.119450

Clarke, P. J., Lawes, M. J., Midgley, J. J., Lamont, B. B., Ojeda, F., Burrows, G. E., et al. (2013). Resprouting as a Key Functional Trait: How Buds, Protection and Resources Drive Persistence after Fire. *New phytol.* 197 (1), 19–35. doi:10.1111/nph.12001

Cortijos-López, M., Navarrete, P. S., de la Parra Muñoz, I., Martínez, T. L., and Romero, M. E. N. (2023). Secuestro de carbono en suelos de media montaña mediterránea mediante la estrategia del desbroce de matorral. *Geogr. cambios, retos Adapt.*, 355–363. doi:10.21138/cg/2023.lc

Cottani, F., and Sabattini, R. A. (2006). Manejo y control de arbustivas en un pastizal con alta carga animal en pastoreo rotativo. *Rev. Científica Agropecu.* 10 (2), 109–120.

Cummings, J., and Smith, D. (2000). The Line-Intercept Method: A Tool for Introductory Plant Ecology Laboratories. *Education* 22.

Davies, G. M., and Gray, A. (2015). Don't Let Spurious Accusations of Pseudoreplication Limit Our Ability to Learn from Natural Experiments (And Other Messy Kinds of Ecological Monitoring). *Ecol. Evol.* 5 (22), 5295–5304. doi:10.1002/ece3.1782

Debouk, H., San Emeterio, L., Marí, T., Canals, R. M., and Sebastià, M. T. (2020). Plant Functional Diversity, Climate and Grazer Type Regulate Soil Activity in Natural Grasslands. *Agronomy* 10 (9), 1291. doi:10.3390/agronomy10091291

Doerr, S. H., Shakesby, R. A., and Walsh, R. P. D. (2000). Soil Water Repellency: Its Causes, Characteristics and Hydro-Geomorphological Significance. *Earth Sci. Rev.* 51 (1–4), 33–65. doi:10.1016/S0012-8252(00)00011-8

Eberhardt, L. L. (1978). Transect Methods for Population Studies. *J. Wildl. Manag.* 42 (1), 1. doi:10.2307/3800685

Eivazi, F., and Tabatabai, M. A. (1988). Glucosidases and Galactosidases in Soils. *Soil Biol. Biochem.* 20 (5), 601–606. doi:10.1016/0038-0717(88)90141-1

Fernández de Ana-Magán, F. J. (2000). El Fuego Y Los Hongos. *1 Cuad. la Soc. Española Ciencias For.* (9), 101–107.

Fierer, N., and Schimel, J. P. (2002). Effects of Drying-Rewetting Frequency on Soil Carbon and Nitrogen Transformations. *Soil Biol. Biochem.* 34 (6), 777–787. doi:10.1016/S0038-0717(02)00007-X

Fontúrbel, M. T., Fernández, C., and Vega, J. A. (2016). Prescribed Burning versus Mechanical Treatments as Shrubland Management Options in NW Spain: Mid-term Soil Microbial Response. *Appl. Soil Ecol.* 107, 334–346. doi:10.1016/j.apsoil.2016.07.008

Fontúrbel, M. T., Jiménez, E., Merino, A., and Vega, J. A. (2024). Contrasting Immediate Impact of Prescribed Fires and Experimental Summer Fires on Soil Organic Matter Quality and Microbial Properties in the Forest Floor and Mineral Soil in Mediterranean Black Pine Forest. *Sci. Total Environ.* 907, 167669. doi:10.1016/j.scitotenv.2023.167669

Francos, M., Pereira, P., Mataix-Solera, J., Arcenegui, V., Alcañiz, M., and Úbeda, X. (2018). How Clear-Cutting Affects Fire Severity and Soil Properties in a Mediterranean Ecosystem. *J. Environ. Manag.* 206, 625–632. doi:10.1016/j.jenvman.2017.11.011

Frazer, D. W., McColl, J. G., and Powers, R. F. (1990). Soil Nitrogen Mineralization in a Clearcutting Chronosequence in a Northern California Conifer Forest. *Soil Sci. Soc. Am. J.* 54 (4), 1145–1152. doi:10.2136/sssaj1990.03615995005400040038x

García Lucas, E. (2013). *Estrategias para la recuperación de suelos degradados en ambientes semiáridos: adición de dosis elevadas de residuos orgánicos de origen urbano y su implicación en la fijación de carbono*. Doctoral Dissertation. Murcia, España: Universidad de Murcia, 363.

Garnica, J. G. F., and Solorio, J. D. D. B. (1995). Efecto de las quemas prescritas sobre algunas características del suelo en un rodal de pino. *Rev. Mex. Ciencias For.* 20 (77), 113–128.

Gelabert, P. J., Rodrigues, M., de la Riva, c, Ameztegui, A., Sebastià, M. T., and Vega-Garcia, C. (2021). LandTrendr Smoothed Spectral Profiles Enhance Woody Encroachment Monitoring. *Remote Sens. Environ.* 262, 112521. doi:10.1016/j.rse.2021.112521

Ghani, A., Dexter, M., and Perrott, K. W. (2003). Hot-water Extractable Carbon in Soils: A Sensitive Measurement for Determining Impacts of Fertilisation, Grazing and Cultivation. *Soil Biol. Biochem.* 35 (9), 1231–1243. doi:10.1016/S0038-0717(03)00186-X

Girona-García, A., Ortiz-Perpiñá, O., and Badía-Villas, D. (2019). Dynamics of Topsoil Carbon Stocks after Prescribed Burning for Pasture Restoration in Shrublands of the Central Pyrenees (NE-Spain). *J. Environ. Manag.* 233, 695–705. doi:10.1016/j.jenvman.2018.12.057

Girona-García, A., Ortiz-Perpiñá, O., Badía-Villas, D., and Martí-Dalmau, C. (2018). Effects of Prescribed Burning on Soil Organic C, Aggregate Stability and Water Repellency in a Subalpine Shrubland: Variations Among Sieve Fractions and Depths. *Catena* 166, 68–77. doi:10.1016/j.catena.2018.03.018

González-Pérez, J. A., González-Vila, F. J., Almendros, G., and Knicker, H. (2004). The Effect of Fire on Soil Organic Matter—A Review. *Environ. Int.* 30 (6), 855–870. doi:10.1016/j.envint.2004.02.003

Hamman, S. T., Burke, I. C., and Knapp, E. E. (2008). Soil Nutrients and Microbial Activity after Early and Late Season Prescribed Burns in a Sierra Nevada Mixed Conifer Forest. *For. Ecol. Manag.* 256 (3), 367–374. doi:10.1016/j.foreco.2008.04.030

Hammer, D. A. T., Ryan, P. D., Hammer, Ø., and Harper, D. A. T. (2001). Past: Paleontological Statistics Software Package for Education and Data Analysis. Available at: http://palaeo-electronica.orghttp://palaeo-electronica.org/2001_1/past/issue1_01.htm.

Hart, S. C., DeLuca, T. H., Newman, G. S., MacKenzie, M. D., and Boyle, S. I. (2005). Post-Fire Vegetative Dynamics as Drivers of Microbial Community Structure and Function in Forest Soils. *For. Ecol. Manag.* 220 (1–3), 166–184. doi:10.1016/j.foreco.2005.08.012

Hashimoto, S., and Suzuki, M. (2004). The Impact of Forest Clear-Cutting on Soil Temperature: A Comparison between before and after Cutting, and between Clear-Cut and Control Sites. *J. For. Res.* 9 (2), 125–132. doi:10.1007/s10310-003-0063-x

Heiri, O., Lotter, A. F., and Lemcke, G. (2001). Loss on Ignition as a Method for Estimating Organic and Carbonate Content in Sediments: Reproducibility and Comparability of Results. *J. Paleolimnol.* 25 (1), 101–110. doi:10.1023/A:1008119611481

Hobley, E. U., Brereton, A. J. L. G., and Wilson, B. (2017). Forest Burning Affects Quality and Quantity of Soil Organic Matter. *Sci. Total Environ.* 575, 41–49. doi:10.1016/j.scitotenv.2016.09.231

Huhta, V. (1976). Effects of Clear-Cutting on Numbers, Biomass and Community Respiration of Soil Invertebrates. *Ann. Zool. Fenn.* 131 (1), 63–80.

Hynes, H. M., and Germida, J. J. (2013). Impact of Clear Cutting on Soil Microbial Communities and Bioavailable Nutrients in the LFH and Ae Horizons of Boreal Plain Forest Soils. *For. Ecol. Manag.* 306, 88–95. doi:10.1016/j.foreco.2013.06.006

Instituto Geológico y Minero de España (IGME) (1972). *Mapa geológico de España – Broto*. IGME. Available at: https://info.igme.es/cartografiadigital/datos/magna50/pdfs/d1_G50/Magna50_178.pdf (Accessed June 20, 2024).

IUSS Working Group WRB (2022). "World Reference Base for Soil Resources," in *International Soil Classification System for Naming Soils and Creating Legends for Soil Maps*. 4th Edn. (Vienna, Austria: International Union of Soil Sciences (IUSS)).

Kalbitz, K., Solinger, S., Park, J. H., Michalzik, B., and Matzner, E. (2000). Controls on the Dynamics Dissolved Organic Matter in Soils: A Review. *Soil Sci.* 165 (4), 277–304. doi:10.1097/00010694-200004000-00001

Kemper, W. D., and Koch, E. J. (1966). "Aggregate Stability of Soils from Western United States and Canada," in *Measurement Procedure, Correlation with Soil Constituents* (Washington, DC: United State Department of Agriculture).

Klute, A. (1986). *Methods of Soil Analysis. Part 1. Physical and Mineralogical Methods*. 2on. ed. A.S.A. - S.S.S.A. Madison, Wisconsin.

Knicker, H. (2007). How Does Fire Affect the Nature and Stability of Soil Organic Nitrogen and Carbon? A Review. *Biogeochemistry* 85 (1), 91–118. doi:10.1007/s10533-007-9104-4

Komac, B., Alados, C., and Camarero, J. (2011). Influence of Topography on the Colonization of Subalpine Grasslands by the Thorny Cushion Dwarf *Echinospartum Horridum*. *Arct. Antarct. Alp. Res.* 43 (4), 601–611. doi:10.1657/1938-4246-43.4.601

Koner, S., Chen, J. S., Hsu, B. M., Tan, C. W., Fan, C. W., Chen, T. H., et al. (2021). Assessment of Carbon Substrate Catabolism Pattern and Functional Metabolic Pathway for Microbiota of Limestone Caves. *Microorganisms* 9 (8), 1789. doi:10.3390/microorganisms9081789

Lasanta, T. (2019). Gestión Activa Frente a Matorralización: Buscando el Equilibrio Entre Conservación y Explotación en Montaña. *Cuad. Investig. Geográfica* 45 (2), 423–440. doi:10.18172/cig.3726

Liang, G., Hui, D., Wu, X., Wu, J., Liu, J., Zhou, G., et al. (2016). Effects of Simulated Acid Rain on Soil Respiration and its Components in a Subtropical Mixed Conifer and Broadleaf Forest in Southern China. *Environ. Sci. Process. Impacts* 18 (2), 246–255. doi:10.1039/c5em00434a

Lombao, A., Barreiro, A., Fontúrbel, M. T., Martín, A., Carballas, T., and Díaz-Raviña, M. (2020). Key Factors Controlling Microbial Community Responses after a Fire: Importance of Severity and Recurrence. *Sci. Total Environ.* 741, 140363. doi:10.1016/j.scitotenv.2020.140363

Lombao, A., Barreiro, A., Fontúrbel, M. T., Martín, A., Carballas, T., and Díaz-Raviña, M. (2021). Effect of Repeated Soil Heating at Different Temperatures on Microbial Activity in Two Burned Soils. *Sci. Total Environ.* 799, 149440. doi:10.1016/j.scitotenv.2021.149440

Lozano, E. (2015). *Sensibilidad de la Glomalina a los Efectos Provocados por el Fuego en el Suelo y su Relación con la Repelencia al Agua en Suelos Forestales Mediterráneos (Doctoral Dissertation, Universidad Miguel Hernández de Elche)*.

Magurran, A. E. (2013). *Ecological Diversity and its Measurement*. Dordrecht: Springer Science & Business Media, 177.

Martínez, O., Valenzuela, E., and Godoy, R. (2006). Poblaciones viables y grupos funcionales de hongos presentes en suelos de bosque de Araucaria-Nothofagus post-incendio. *Bol. Micológico* 21. doi:10.22370/bolmicol.2006.21.0.258

Martínez Romero, A., and Leyva Galán, A. (2014). La biomasa de los cultivos en el ecosistema. Sus beneficios agroecológicos -. *Cultiv. Trop.* 35 (1).

Mataix-Solera, J., Cerdà, A., Arcenegui, V., Jordán, A., and Zavala, L. M. (2011). Fire Effects on Soil Aggregation: A Review. *Earth-Science Rev.* 109 (1-2), 44–60. doi:10.1016/j.earscirev.2011.08.002

Mataix-Solera, J., Guerrero, C., García-Orenes, F., Bárcenas, G. M., and Torres, M. P. (2009). "Forest Fire Effects on Soil Microbiology," in *Fire Effects on Soils and Restoration Strategies*. doi:10.1201/9781439843338-c5

Montserrat, P., Montserrat Martí, J. M., and Montserrat-Martí, G. (1984). Estudio de las comunidades de *Echinospartum horridum* en el Pirineo español. *Acta Biol. Montserrat.* 4 (IV), 249–257.

Mora, J. L., Badía–Villas, D., and Gómez, D. (2022). Fire Does Not Transform Shrublands of *Echinospartum horridum* (Vahl) Rothm. Into Grasslands in the Pyrenees: Development of Community Structure and Nutritive Value after Single Prescribed Burns. *J. Environ. Manag.* 315, 115125. doi:10.1016/j.jenvman.2022.115125

Moya, D., Fonturbel, T., Peña, E., Alfaro-Sanchez, R., Plaza-Álvarez, P. A., González-Romero, J., et al. (2022). Fire Damage to the Soil Bacterial Structure and Function Depends on Burn Severity: Experimental Burnings at a Lysimetric Facility (MedForECOtron). *Forests* 13 (7), 1118. doi:10.3390/f13071118

Múgica, L., Le Roux, X., San Emeterio, L., Cantarel, A., Durán, M., Gervaix, J., et al. (2024). Pyric Herbivory Decreases Soil Denitrification Despite Increased Nitrate Availability in a Temperate Grassland. *J. Environ. Manag.* 365, 121695. doi:10.1016/j.jenvman.2024.121695

Muñoz-Iniestra, D. J., López, G. F., Hernández, M. M., Soler, A. A., and López, G. J. (2009). Impacto de la pérdida de la vegetación sobre las propiedades de un suelo aluvial. *Terra Latinoam.* 27 (3), 237–246.

Nadal-Romero, E., Otal-Laín, I., Lasanta, T., Sánchez-Navarrete, P., Errea, P., and Cammeraat, E. (2018). Woody Encroachment and Soil Carbon Stocks in Subalpine Areas in the Central Spanish Pyrenees. *Sci. Total Environ.* 636, 727–736. doi:10.1016/j.scitotenv.2018.04.324

Nadal-Romero, E., Rubio, P., Kremyda, V., Absalah, S., Cammeraat, E., Jansen, B., et al. (2021). Effects of Agricultural Land Abandonment on Soil Organic Carbon Stocks and Composition of Soil Organic Matter in the Central Spanish Pyrenees. *Catena* 205, 105441. doi:10.1016/j.catena.2021.105441

Page, A. L., Miller, R. H., and Keeney, D. R. (1982). "Methods of Soil Analysis. Part 2," in *Chemical and Microbiological Methods*. 2on. ed. A.S.A. - S.S.S.A. Madison, Wisconsin.

Pereira, J. S., Badía, D., Martí, C., Mora, J. L., and Donzeli, V. P. (2023). Fire Effects on Biochemical Properties of a Semiarid Pine Forest Topsoil at Cm-Scale. *Pedobiologia* 96, 150860. doi:10.1016/j.pedobi.2022.150860

Pietikäinen, J., and Fritze, H. (1995). Clear-Cutting and Prescribed Burning in Coniferous Forest: Comparison of Effects on Soil Fungal and Total Microbial Biomass, Respiration Activity and Nitrification. *Soil Biol. Biochem.* 27 (1), 101–109. doi:10.1016/0038-0717(94)00125-K

Pineda, M. E. B., and Lizarazo-Forero, L. M. (2013). Grupos funcionales de microorganismos en suelos de páramo perturbados por incendios forestales. *Rev. Ciencias* 17 (2), 121–136.

Rillig, M. C., Wright, S. F., Nichols, K. A., Schmidt, W. F., and Torn, M. S. (2001). Large Contribution of Arbuscular Mycorrhizal Fungi to Soil Carbon Pools in Tropical Forest Soils. *Plant Soil* 233 (2), 167–177. doi:10.1023/A:1010364221169

Rovira, P., and Ramón Vallejo, V. (2007). Labile, Recalcitrant, and Inert Organic Matter in Mediterranean Forest Soils. *Soil Biol. Biochem.* 39 (1), 202–215. doi:10.1016/j.soilbio.2006.07.021

Rutgers, M., Wouterse, M., Drost, S. M., Breure, A. M., Mulder, C., Stone, D., et al. (2016). Monitoring Soil Bacteria with Community-Level Physiological Profiles Using Biolog™ ECO-Plates in the Netherlands and Europe. *Appl. Soil Ecol.* 97, 23–35. doi:10.1016/j.apsoil.2015.06.007

San Emeterio, L., Múgica, L., Ugarte, M. D., Goicoa, T., and Canals, R. M. (2016). Sustainability of Traditional Pastoral Fires in Highlands under Global Change: Effects on Soil Function and Nutrient Cycling. *Agric. Ecosyst. Environ.* 235, 155–163. doi:10.1016/j.agee.2016.10.009

San-Emeterio, L. M., Lozano, E., Arcenegui, V., Mataix-Solera, J., Jiménez-Morillo, N. T., and González-Pérez, J. A. (2024). Soil-Easily Extractable Glomalin: An Innovative Approach to Deciphering its Molecular Composition under the Influence of Seasonality, Vegetation Cover, and Wildfire. *Environ. Sci. & Technol.* 58, 22624–22634. doi:10.1021/acs.est.4c10036

Santín, C., and Doerr, S. H. (2016). Fire Effects on Soils: The Human Dimension. *Philosophical Trans. R. Soc. B Biol. Sci.* 371 (1696), 20150171. doi:10.1098/rstb.2015.0171

Sardans, J., Peñuelas, J., and Estiarte, M. (2008). Changes in Soil Enzymes Related to C and N Cycle and in Soil C and N Content under Prolonged Warming and Drought in a Mediterranean Shrubland. *Appl. Soil Ecol.* 39 (2), 223–235. doi:10.1016/j.apsoil.2007.12.011

Schirpke, U., Kohler, M., Leitinger, G., Fontana, V., Tasser, E., and Tappeiner, U. (2017). Future Impacts of Changing Land-Use and Climate on Ecosystem Services of Mountain Grassland and Their Resilience. *Ecosyst. Serv.* 26, 79–94. doi:10.1016/j.ecoser.2017.06.008

Simón, L., Hernández, M., Reyes, F., and Sánchez, S. (2005). Efecto de las leguminosas arbóreas en el suelo y en la productividad de los cultivos acompañantes. *Pastos Forrajes* 28 (1), 29–45.

Sinsabaugh, R. L., Lauber, C. L., Weintraub, M. N., Ahmed, B., Allison, S. D., Crenshaw, C., et al. (2008). Stoichiometry of Soil Enzyme Activity at Global Scale. *Ecol. Lett.* 11 (11), 1252–1264. doi:10.1111/j.1461-0248.2008.01245.x

Staddon, W. J., Duchesne, L. C., and Trevors, J. T. (1997). Microbial Diversity and Community Structure of Postdisturbance Forest Soils as Determined by Sole-Carbon-Source Utilization Patterns. *Microb. Ecol.* 34, 125–130. doi:10.1007/s002489900042

Tokarczyk, N. (2017). Forest Encroachment on Temperate Mountain Meadows. Scale, Drivers and Current Research Directions. *Geogr. Pol.* 90 (4), 463–480. doi:10.7163/GPol.0112

Torres, L. G., and Cabrera, A. H. (2005). "La agricultura de conservación y sus beneficios," in *Protección del suelo y el desarrollo sostenible: Seminario Europeo: Soria, 15-17 de mayo de 2002* (Madrid, España: Instituto Geológico y Minero de España), 91–100.

Vadillo, J. A., Flaño, P. R., Monreal, N. L. R., Romero, M. E. N., Martínez, T. L., and Cortijos-López, M. (2023). "Comportamiento de la Infiltración del Suelo en Diferentes Cubiertas Vegetales y Usos del Suelo en la Media Montaña Mediterránea," in *Geografía: Cambios, Retos y Adaptación: Libro de Actas. XVIII Congreso de la Asociación Española de Geografía, Logroño, 12 al 14 de Septiembre de 2023* (Madrid, España: Asociación Española de Geografía), 291–300.

Verma, S., and Jayakumar, S. (2012). Impact of Forest Fire on Physical, Chemical and Biological Properties of Soil: A Review. *Proc. Int. Acad. Ecol. Environ. Sci.* 2 (3), 168.

Wright, S. F., and Upadhyaya, A. (1996). Extraction of an Abundant and Unusual Protein from Soil and Comparison with Hyphal Protein of Arbuscular Mycorrhizal Fungi. *Soil Sci.* 161 (9), 575–586. doi:10.1097/00010694-199609000-00003

Zavala, L. M. M., de Celis Silvia, R., and López, A. J. (2014). How Wildfires Affect Soil Properties. A Brief Review. *Cuadernos de investigación geográfica Geogr. Res. Lett.* 40 (2), 311–331. doi:10.18172/cig.2522

ORIGINAL RESEARCH
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Impact of Irrigation Management on Salinity and Volume of Drainage Water in an 8000 ha Irrigation District in the Ebro Basin (NE Spain)

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When irrigation is introduced in a region, it adds salts and mobilizes those already present in the soil, changing the soil-plant-atmosphere continuum. These changes may lead to higher salt loads in the drainage water which, in turn, can have an impact on waters further downstream. Knowing the dynamics of these loads at the sub-basin scale is key to accounting for the possible impact that irrigation may have and to determining what improvements could be applied. This study aimed to characterise the different salt types present and to investigate drainage salt loads and their dependence upon irrigation input and their implications in irrigation management in a new, and well-managed, 8000 ha irrigation district located in the Ebro basin, NE Spain. In addition, it is relevant to highlight that the Ebro basin suffered a period of significant drought in 2023. As a result, irrigation restrictions were applied in many irrigation districts. We sought to investigate how these reductions influenced irrigation return flows and salt discharges within a selected irrigation district. The present study was undertaken during the irrigation periods of 2021, 2022, and 2023. We monitored water inputs and outputs in two representative sub-basins belonging to the Algerri-Balaguer irrigation district (Ebro basin, NE Spain). We also analysed water inputs and outputs in order to characterise and establish the salt balances in both of the sub-basins that we studied. Our results showed that during 2023, a reduction in irrigation delivery of 31% led to a reduction in drainage volume of 73%, resulting in a decrease in salt exports through drainage of 70%. These data revealed that the application of irrigation restrictions not only led to an increased availability of downstream water resources, but also to a decrease in drainage volume and salt load, resulting in an improvement in irrigation management by farmers. However, it should also be underlined that this drastic reduction in irrigation was, in turn, responsible for a reduction in yield. Re-utilising drainage waters and/or improving irrigation management at the field scale may help to find this point of balance in areas with high water demands.

Keywords: return flows, water quality, drought, calcareous soils, environmental impact

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INTRODUCTION

The introduction of irrigation in a region has a significant impact on the natural dynamics of its environment, including its soils (Murray and Grant, 2007; Hillel et al., 2008; Cox et al., 2018). In Mediterranean areas, irrigation plays a crucial role in enabling high crop yields and promoting social and economic development (FAO, 2002). These areas typically have soils that are rich in ions, because the dry climate prevents them from being washed out. The aridity of their climates is characterized by low levels of precipitation (P) compared to evapotranspiration (ET) (Soil Survey Staff, 2022). Under dry-land conditions, the balance between evapotranspiration and precipitation leads to a deficit in water availability in the soil and there is little possibility of salt leaching. The application of irrigation water leads to a significant change in soil water dynamics. Irrigation, which may also contain high levels of dissolved salts, allows excess water to carry salts away from the root zone more efficiently. The movement of water from the soil to lower areas, aided by drainage systems, facilitates the removal of salts from both the irrigated fields and the entire irrigated area. This, helps to prevent soil salinisation and water-logging (Fereres et al., 2011).

Numerous studies have been conducted to address this issue. In irrigated Mediterranean regions, and specifically in the Ebro basin, salt removal in irrigated land has been reported to range from 0.5 (Andrés and Cuchí, 2014) to 14.5 t. ha^{-1}. year^{-1} (Abrahao et al., 2011; Barros et al., 2015; Causapé et al., 2004a; García-Garizábal et al., 2009; 2012; Isidoro et al., 2006; Tedeschi et al., 2001). The variations in these values can primarily be attributed to the type of irrigation system used (surface or sprinkler) and the presence of salts in the soils of the area, which are influenced by geology, geomorphology, and hydrology. A notable example of such differences was highlighted in a study conducted by (Jiménez-Aguirre and Isidoro, 2018), who compared the salinity and volume of the drainage water (that constitute what will be the salt loads) in an irrigation district before (with surface irrigation) and after modernization (with sprinkler). That study revealed a 60% reduction in salt loads, from 16.7 t. ha^{-1}. year^{-1} to 5.6 t. ha^{-1}. year^{-1}, as a result of reducing the water input through irrigation by 5,536 m^3. ha^{-1}. year^{-1}.

Understanding the quality and quantity of drainage water within an irrigation district is crucial for determining opportunities for water reuse, evaluating potential impacts on water bodies, and assessing the sustainability of irrigation practices related to soil and water quality.

It is on these questions that this study is focused. We wanted to investigate how a reduction in irrigation water use affects salinity and volume of drainage water in new irrigated areas where land consolidation has been carried out and a drainage network has been designed to allow for monitoring. To do so, this study focused on an irrigation district that, due to the drought in the Ebro basin, suffered a 25% restriction (from a theoretical maximum allocation of 48 hm^3 to 36 hm^3) in irrigation in 2023. During the years 2021, 2022, and 2023, we obtained both qualitative and quantitative data about the irrigation, precipitation in, and drainage from, the Algerri-Balaguer irrigation district (Ebro basin, NE Spain) at the sub-basin scale. Our objective was not only to assess the salt balances but also to understand how the irrigation-precipitation-drainage system responds to reduced water inputs during hydrological drought restrictions. We also conducted a comprehensive analysis of water quality parameters relating to the drainage water in order to assess its potential for reuse in irrigation and any potential downstream impacts.

MATERIAL AND METHODS

Area Studied

Land Use and Irrigation Management in the Area Studied

The research area is located in the Algerri-Balaguer irrigation district, which is part of the River Ebro basin in northeastern Spain. This district was established in 1998 and has a total irrigable area of 8,000 ha.

The maximum water usage in this district is 48 hm^3. year^{-1}. The irrigation water used in this district is pumped from the River Noguera Ribagorçana (see **Figure 1**), on a daily basis, as needed. Not all land within the irrigation district is irrigated. The total irrigated area has been ranging from 6,000 to 7,000 ha over the years, depending on the fallow requirements and water availability (6,243 ha, 6326 ha, 6345 ha, for 2021, 2022, and 2023, respectively). All of the irrigation facilities in this district are pressurized, with 70% of irrigation using sprinkler systems and 30% using drip irrigation.

The predominant land use in this district is double cropping, with winter cereals or peas (to a lesser degree) being grown in winter, followed by maize in summer. Double cropping accounts for over 50% of land use in the irrigated area. Orchard crops, such as apples, almonds and olives, are also grown in this district.

To conduct the study within the irrigation district, four drainage sub-basins were selected. These were defined using the "Fill sinks" (Wang and Liu, 2006) algorithm in QGIS 3.24.3 software. The digital elevation model of the study zone used for this purpose was obtained from Institut Cartogràfic i Geològic de Catalunya (2020). The "SAGA Terrain Analysis: Channel Network and Drainage Basins" toolbox was then used to obtain the final drainage sub-basin areas. The specific drainage sub-basins can be seen in **Figure 1**; **Table 1**.

The extension, land use and acreage of the sub-basins which were studied are shown in **Table 1**. Land use data were obtained from the DUN-SIGPAC data set provided by the Departament d'Acció Climàtica (2021) and validated, for each study year, using *in situ* data provided by technicians working in the Algerri-Balaguer irrigation district.

Weather and Climate

The study area has a dry, continental Mediterranean climate, with cold winters and hot, dry summers. Its average air temperature is 14.4°C. Its average annual rainfall and reference evapotranspiration are 378 mm and 1,072 mm, respectively (2000–2022), as measured at the agrometeorological station of Albesa (RuralCat Departament d'Acció Climàtica Alimentació i Agenda Rural, 2023). Rainfall is predominantly concentrated

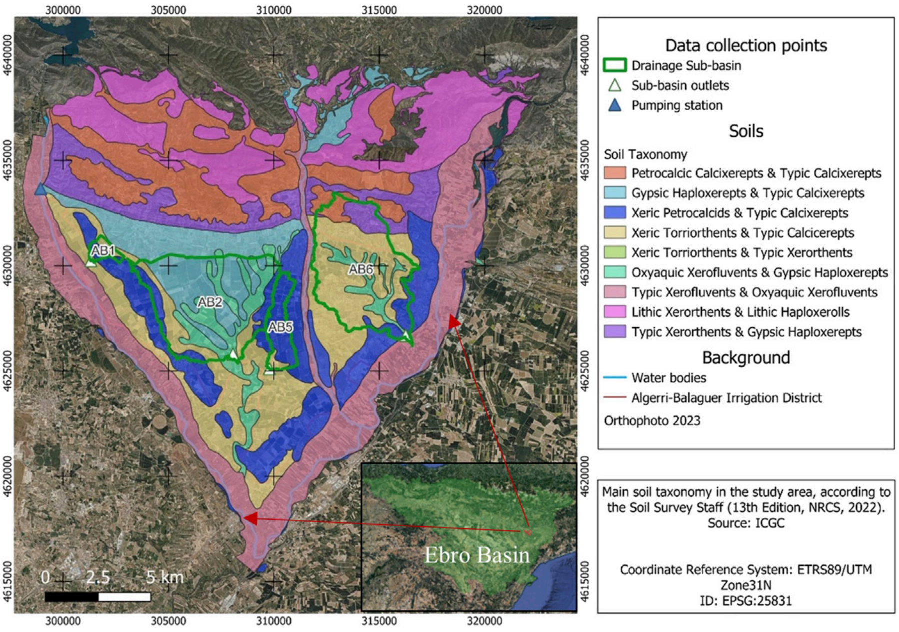

FIGURE 1 | The sub-basins studied, main soil mapping units in the study area, and data collection points.

TABLE 1 | Catchment area and land use in the four sub-basins studied within the Algerri-Balaguer irrigation district.

Land use (ha)	AB1	AB2	AB5	AB6	Total
Catchment area	114	2,587	419	2,648	5,768
Irrigated area	94	2,337	374	925	3,731
Double crop	61	1,323	215	319	1918
Orchard trees	17	344	23	97	481
Alfalfa		159	16	79	254
Maize		158	23	97	278
Winter cereal		205	69	294	568
Others	16	147	29	40	232

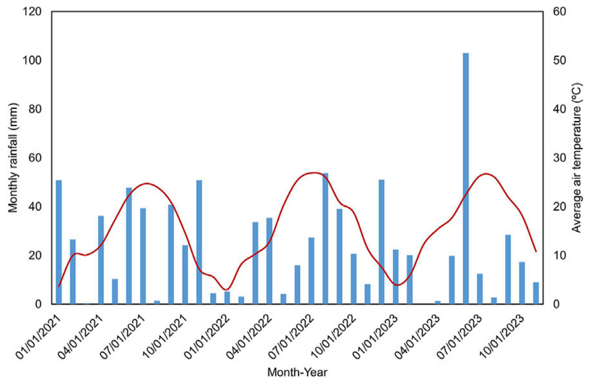

FIGURE 2 | Monthly rainfall and average air temperature in the study area during the study period, according to the agrometeorological station at Albesa.

during the spring and autumn seasons. During the study period, annual rainfall was below average, with values of 333, 298, and 237 mm, for 2021, 2022, and 2023, respectively (**Figure 2**).

Geology and Soils

From a geological point of view, the study site is located in the Piedmont zone, between the expansive Pre-Pyrenean Mountain system, which is characterised by imposing mountain ranges, and the Tertiary depression, which is dominated by the Ebro Valley. Serra Llarga marks its northern boundary, corresponding to the southern slopes of the Barbastro-Balaguer Anticline, with the Alfarràs plateau connecting it to lower-lying areas through fluvial deposits and glacis. To the south, the study area is bordered by the central-eastern depression, which is traversed by the Segre and Noguera Ribagorçana rivers, which have formed prominent, stepped terraces.

Geologically, the region's stratigraphy comprises Tertiary materials, which progress from a gypsum base and include two detrital units. The lower unit includes stratified limestones, marls, flint intercalations, sandstones alternating with silts and clays, and carbonate levels. Upon this lies the upper detrital unit, which features paleochannel deposits of sandstones, silts, and red clays, alternating with sandstone bars and conglomerates. Quaternary deposits, characterised by terraces and colluvial deposits have also been identified in the study area (Gil et al., 1998).

Hydrologically, the study region falls within the basins of the rivers Segre and Noguera Ribagorçana. In terms of hydrogeology, the aquifer system of the Ebro's alluvial terraces, is divided into two aquifers: the lower alluvial terrace of the River Noguera Ribagorçana, with its current floodplain, and the last alluvial terrace of the River Segre. In both cases, the impermeable substrate consists of tertiary lithologies, such as clays, gypsum, and silts. Recharge mechanisms encompass direct infiltration from rivers, rainwater infiltration, limited infiltration from lateral torrents, and predominant infiltration from irrigation returns (Mensua et al., 1977).

However, this aquifer system is not extensive in the studied sub-basins, as it is confined to the terraces of rivers Noguera Ribagorçana, Farfanya, and Segre (areas limited by Typic Xerofluvents and Oxyaquic Xerofluvents, in **Figure 1**). Thus, there is no interaction with groundwater in the study area.

The soils in the study area have been widely studied. Field studies dating from 1984–1986; 1990–1991; 1994; and 2017–2018 resulted in a detailed 1:25,000 soil map (Institut Cartogràfic i Geològic de Catalunya, 2019), which is available online.

The soils in the Algerri Balaguer irrigation district have pHs ranging from of 7.6–8.5, with high levels of calcium carbonate (15%–50%) and low levels of organic matter (0.2%–3%). The soil textures are mainly loam, clay-loam, silt, and silty-clay-loam. Soil depths vary, being generally deep (> 120 cm) and well-drained, and there is no evidence of redox reactions in the first 100 cm of the soil profile (Boixadera et al., 1989), indicating that there is no (and has not been) shallow water-table.

Secondary accumulations of calcium carbonate often manifest as nodules (calcic horizons), and in cases where coarse elements are abundant, petrocalcic horizons may form. It is also common to find crystals and secondary accumulations of vermiform gypsum, which have formed gypsic horizons. This has occurred in soils that have developed on detrital materials originating from the residual platforms of alluvial deposits in the foothills of the Serra Llarga range. According to the parental material, there are also distinctive sequences of horizons, with the most common ones being Ap - Bwkn(y)/Bw/Bkm/By - 2C/2R.

The soils in the study area are mainly classified as Gypsic Haploxerepts, Typic Calcixerepts, Xeric Torriorthents or Xeric Petrocalcids, among others, according to the Soil Survey Staff (Soil Survey Staff, 2022). Further information on the different soil taxonomies present in the area can be found in **Figure 1**.

Sampling Methodology

Throughout 2021, 2022, and 2023, the volumes of irrigation water used, precipitation and the amount of water drained were measured. Complete water analyses were also carried out periodically in order to determine the main quality parameters.

Irrigation Water

As already mentioned in 2.1.1, the Algerri-Balaguer irrigation district has a maximum water use of 48 hm^3. $year^{-1}$. This water comes from the River Noguera Ribagorçana. Demands for water from the irrigation district are submitted on a daily basis to the Confederación Hidrográfica del Ebro (CHE), which is the institution responsible for the management of water in the River Ebro basin. Once the requested water has been delivered from the upstream reservoir (Santa Ana dam), it is recorded in the Ebro Automatic Hydrological Information System (Sistema Automático de Información Hidrológica – SAIH), whose data are available online (SAIH, last access 15th December 2023). Once the water is pumped from the river to the canal, it is stored in a regulating reservoir and later on distributed throughout the irrigation district, between different reservoirs, as illustrated in **Figure 3**.

The farmers connect their systems to the irrigation district network of hydrants, which are equipped with flow-measuring devices. A total of 1,369 hydrants were installed in the Algerri Balaguer irrigation district during its development. Non-revenue water (NRW), which is also known as unregistered water, is the difference between the volume of water pumped into the water distribution system and that which reaches the hydrant. It has been estimated as representing 8% in 2021 and 2022 (Olivera-Guerra et al., 2023) and 7% in 2023.

The Algerri-Balaguer irrigation season starts on 5th March and ends on 15th October. To monitor yearly water use and provide a tool for water accounting, each hydrant is checked before the start and after the end of the irrigation season. This enables the irrigation district technicians to accurately monitor the amount of irrigation water used from each hydrant and its associated field. The irrigation district makes two charges for supplying water. One is fixed and depends on the total acreage irrigated and the other is variable and depends on the total volume of water used.

With this information, and knowing the location of each hydrant, it is possible to determine the total irrigation water input for each sub-basin and year. In addition, it is possible to obtain average values of water consumption for each crop as recorded at the hydrant.

The total amount of water used per sub-basin and day can be determined by considering both the daily volume of pumped water and the yearly use per hydrant. We assume that daily pattern water consumption is consistent across all the sub-basins studied.

Monitoring Drainage Volume and Water Quality

During the 2021, 2022, and 2023 irrigation seasons, the water level and electrical conductivity (EC) at the outlets from the four sub-basins (**Figure 1**) were continuously monitored, using a Hydros21 sensor (METERGroup, USA). This sensor provides hourly average data about water level (mm), electrical conductivity (EC, $dS \cdot m^{-1}$), and water temperature (°C). The flow data at the drain outlets are obtained from the water level according to the procedure described in Altés et al. (2023). By applying this methodology, it is possible to obtain hourly flow values (e.g., $m^3 \cdot h^{-1}$). Technical information regarding the Hydros21 Sensor can be obtained online in METERGroup.

However, among the four sub-basins, reliable flow estimates are only available for outlets AB1 and AB2, which were used for determining the salt and water balances. When characterising the quality of the drainage water, data from all of the four monitored sub-basin were used.

Drainage water quality was monitored in two different ways. On the one hand, continuous hourly EC ($dS \cdot m^{-1}$) values were registered using the HYDROS21 sensor; on the other, six-monthly ion analyses were performed in the laboratory for the four sub-basin outlets and irrigation water. The latter was done using the UNE-EN ISO 10304-1, UNE-EN ISO 10304-4 and

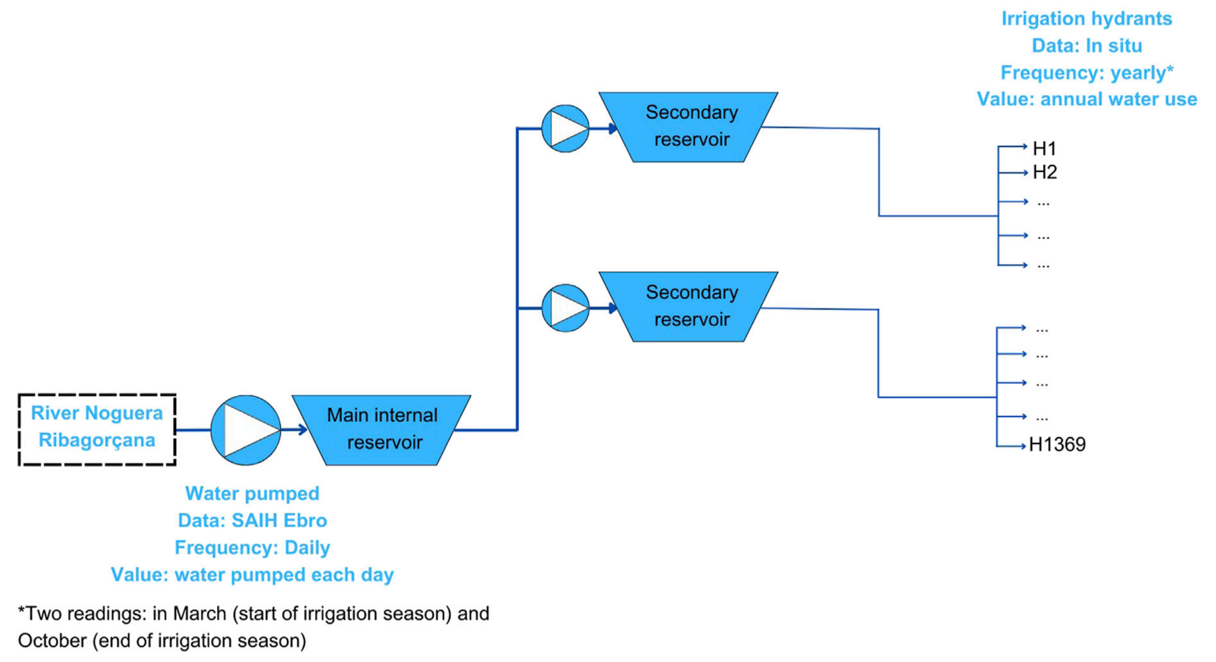

FIGURE 3 | Diagram showing the irrigation network of the Algerri Balaguer irrigation district and the points from which the water volume data were collected.

UNE-EN ISO 11885 methodologies. This allowed us to correlate continuous EC values with values for total dissolved ions (TDI) (mg·L^{-1}). With this value, combined with the outflows at the outlets, we were able to know the total salt export during the period studied.

Salt Balances

A total of six salt balances were carried out. Three were obtained for sub-basin AB1 and another three for sub-basin AB2. They were obtained for the irrigation periods in the years 2021, 2022, and 2023: from 5th March to 15th October in each year.

The salt balance (ΔSB) equation was defined by the difference between salt inputs (SI) and outputs (SO). This is a common methodology and has been used in other studies conducted in the Ebro basin, such as (Andrés and Cuchí, 2014; Causapé et al., 2004a).

In the case of the present study, the main salt inputs were irrigation (SI$_I$) and rainfall (SI$_R$). In the case of irrigation, total dissolved ions (TDI, mg·L^{-1}) were obtained from the relationship between EC and the sum of all the ions obtained in the laboratory analysis. In that of precipitation TDI, there was no locally available data. To fill this gap, we used average data from other salt balance studies conducted in the Ebro basin in recent decades. All of these concluded that the contribution of rain salts to the total balance was low, and never greater than 5% [(Andrés and Cuchí, 2014; Causapé et al., 2004b; Quílez, 1985)].

It should be noted that salt exports (SO) correspond exclusively to the salt load of the drainage water, as other components of the balance, such as salt removal by crop uptake, are considered negligible. In the case of groundwater, there was no evidence of the aquifers in the sub-basins studied (Agència Catalana de l'Aigua, 2013; Instituto Geológico y Minero de España and Dirección General del Agua, 2010; Ministerio para la Transición Ecológica y el Reto Demográfico, 2022). In these cases, the resulting salt balance would be provided by **Equation 1**.

$$\Delta SB = SI_I + SI_R - SO \quad (1)$$

Water and salt balance calculations were conducted for the entire basin. The results were then divided by the irrigated area, yielding the average salt balance per field, expressed in kg. ha^{-1}. year^{-1}. In this way, it was easier to make comparisons between both of the sub-basins studied and with other similar studies.

We also performed a separate balance calculation for each ion in order to know which ions were exported through drainage water and which remained in the soil.

Leaching Fraction

The leaching fraction (LF) represents the depth of water that leached below the root zone compared to the total depth of water applied (Ayers and Wescot, 1985) and is provided by **Equation 2**. In the case of irrigated agriculture, the total volume of water applied is the sum of irrigation and rainfall. In the present study, the amount of leached water accounts for drainage water.

$$LF(\%) = \frac{Drainage}{Irrigation + Rainfall} \cdot 100 \quad (2)$$

Irrigation adds salts to the soil, which can potentially decrease crop yields in the medium term. Additionally, in calcareous soils, irrigation can dissolve existing salts in the soil. To maintain soil quality, these salts must be removed, a process defined as leaching requirements (LR) (Rhoades, 1974; Doorenbos and Pruitt, 1977; Ayers and Wescot, 1985). As long as the leaching fraction (LF) is

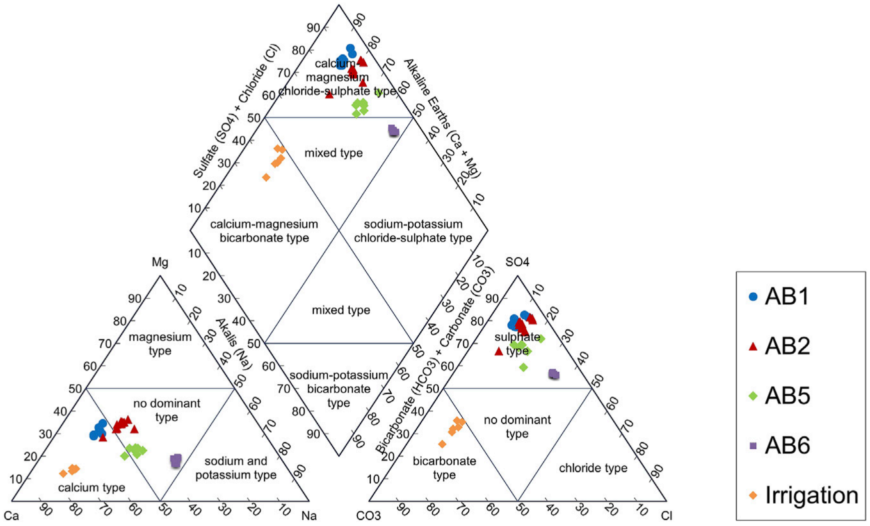

FIGURE 4 | Piper diagram of irrigation water and the different drainage water in the sub-basins studied. Template by (Stosch, 2022).

greater than or equal to the leaching requirement (LR), there will be no accumulation of salts from the irrigation water, and existing salts in the soil will be leached away. If this situation persists for extended periods, salts from irrigation water will accumulate in the soil, leading to processes known as secondary soil salinisation. Amongst other things, this will adversely affect the yields of non-salt-tolerant crops.

In this study, the leaching fractions (LF) were estimated and compared with the leaching requirements (LR), which can be calculated using models. We employed the model proposed by Rhoades (1974) for these estimations, following **Equation 3**,

$$LR(\%) = \frac{EC_i}{5.(EC_e) - EC_i}\cdot 100 \qquad (3)$$

With EC_i being the electrical conductivity of irrigation water, valued at 0.37 dS·m^{-1} in the study area and EC_e the average soil salinity tolerated by the crop, measured from a soil saturation extract. This value can be obtained from Ayers and Wescot (1985) for several crops. Given that maize is one of the most sensitive crops to soil salinity (and the main crop in the area), an electrical conductivity of the saturated soil-paste extract (EC$_e$) of 1.7 dS·m^{-1} was used in the Rhoades model.

According to the Rhoades model, the salt leaching requirement with an irrigation water electrical conductivity of 0.37 dS·m^{-1} and an EC$_e$ of 1.7 dS·m^{-1} is 4.5%. Consequently, if LF ≥ 4.5%, the LR would be achieved and, in theory, no salt build-up should occur.

RESULTS AND DISCUSSION

Water Quality Data

Figure 4 presents the Piper diagram (Piper, 1944) for the four sub-basins studied, along with the irrigation water used in the Algerri-Balaguer.

The Piper diagram is a graphic procedure for geochemical interpretation of water analysis. It is useful for observing and describing possible differences between samples and sources, in terms of their chemistry. It shows the relative proportions of cations and anions and their hydrochemical characteristics.

The Piper diagram illustrates the differences in ionic composition between the irrigation water and the drainage water. In the case of the cations, the irrigation water exhibited a predominance of calcium. In the drainage water, there is no dominant cation type. This discrepancy was primarily due to the elevated levels of Mg^{2+} and Na^{+} in drainage waters and its absence in irrigation (see **Table 2**). In the case of anions, it is clear that different types predominate depending on the water source. While bicarbonate is the primary ion present in irrigation water, sulphates predominate in drainage water.

The irrigation water showed characteristics of a calcium-magnesium bicarbonate type. Conversely, the drainage water exhibited a composition dominated by calcium, magnesium, chlorine, and sulfate ions. However, in the case of AB6, there was a mixed type, attributable to the presence of elevated levels of Na^{+} and Cl^{-}. These ions are present in the soils classified as Xeric Torriorthents that predominate in this sub-basin (**Figure 1**).The differences in composition between the irrigation and drainage waters was a result of the dissolution of salts present in the soil; this process is intensified with higher water inputs, such as the application of irrigation.

On the other hand, we established a relationship between the total dissolved ions –TDI, mg·L^{-1} (Hart, 1974; McNeil and Cox, 2000)–, and the electrical conductivity (EC, dS·m^{-1}) of the water. TDI considers the sum of major ions in the water, expressed in mg. L^{-1}. In most water, these ions correspond to $Ca^{2+}, Mg^{2+}, Na^{+}, Cl^{-}, SO_4^{2-}$ and HCO_3^{-}. This serves as an initial step for determining the salt input through irrigation and salt output through drainage. The relationship between TDI and EC is generally linear, according to **Equation 4**, with values of k ranging between 350 and 1,000 in most waters.

TABLE 2 | Mean and standard deviation of the main ions analysed in the different sample points. Values for ions, expressed in mmol$_c$. L^{-1}. SAR accounts for sodium adsorption ratio and EC for electrical conductivity (dS. m^{-1} at 25°C). The respective number of samples were n = 12 for AB2, n = 8 for AB1 and AB5 and n = 6 for AB6 and irrigation.

Sample point	*Ca^{2+}*	*Mg^{2+}*	*Na^{+}*	*Cl^{-}*	*SO$_4^{2-}$*	*HCO$_3^{-}$*	*SAR*	*EC*
AB1	27.5 ± 3	15.2 ± 1.3	6.6 ± 0.2	4.3 ± 1	35.4 ± 5.8	4.9 ± 1.3	1.4	3.3
AB2	25.3 ± 5.5	18.8 ± 4.9	10.9 ± 3	7.0 ± 2	42.1 ± 10.6	4.6 ± 1.3	2.3	3.7
AB5	15.9 ± 0.8	7.5 ± 0.7	10.1 ± 1.1	5.9 ± 1.1	22.4 ± 2.6	4.5 ± 1	2.9	2.6
AB6	21.6 ± 1.3	11.1 ± 0.7	28.0 ± 1.6	20.2 ± 1.6	33.9 ± 0.7	5.7 ± 0.2	6.9	4.6
Irrigation	3.0 ± 0.2	0.6 ± 0.1	0.5 ± 0.1	0.5 ± 0	1.3 ± 0.1	2.2 ± 0.3	0.4	0.37

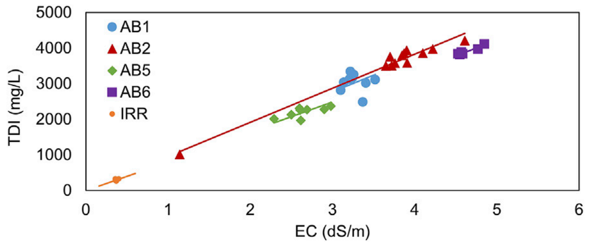

FIGURE 5 | Relationship between total dissolved ions (TDI, mg·L^{-1}) and electrical conductivity (EC, dS·m^{-1}) in the four sub-basins studied and in irrigation water.

$$TDI\left(mg{\cdot}L^{-1}\right) = k \cdot EC\left(dS{\cdot}m^{-1}\right) \tag{4}$$

When assessing most salt balances, it is common to use total dissolved solids (TDS) for this purpose, establishing the relationship at 640 mg·L^{-1} to 1 dS·m^{-1} (Rhoades et al., 1999; USSL, 1954) for continental waters, and commonly reaching values of 890 mg. L^{-1} (Rusydi, 2018). However, total dissolved solids (TDS) includes not only ionic dissolved solids but also organic solids. As our goal was to determine salt inputs and outputs, we used the TDI-EC relationship. Moreover, in waters from xeric regions, originating in calcareous soils with a prevalence of gypsum, it is advisable to establish an *in situ* relationship. Applying the relationship proposed by the USSL may lead to an underestimation of the salt content in drainage water and its environmental impact.

In **Figure 5** we show the TDI-EC relationship for water in the four sub-basins studied and for the irrigation water.

All the relationships were higher than 640 mg·L^{-1}, ranging from 804 (irrigation) to 958 (AB2). The relationships for each site were:

- $TDI\,(AB1) = 926{\cdot}EC\ (R^2_{adj} = 0.87,\ p - value < 0.001)$
- $TDI\,(AB2) = 958{\cdot}EC\ (R^2_{adj} = 0.91,\ p - value < 0.001)$
- $TDI\,(AB5) = 830{\cdot}EC\ (R^2_{adj} = 0.85,\ p - value < 0.001)$
- $TDI\,(AB6) = 842{\cdot}EC\ (R^2_{adj} = 0.80,\ p - value < 0.001)$
- $TDI\,(irrigation) = 804 \cdot EC$ $(R^2_{adj} = 0.79,\ p - value < 0.001)$

In **Table 2**, we also indicate the SAR (sodium adsorption ratio) and EC (electrical conductivity) of each sample site. It is important to note that in AB1, AB,2 and AB5, the SAR values did not exceed 3, while the TDI values ranged between 1,000 and 4,500 mg·L^{-1}. According to the guidelines proposed by Ayers and Wescot (1985), reusing this drainage water for irrigation would not be highly recommended, as they could increase the EC$_e$. However, as seen in **Table 2** and in **Figure 4** the majority of these TDI corresponds to calcium-sulfate (Ca$_2$SO$_4$) and magnesium-sulfate (Mg$_2$SO$_4$) salts, which are not very soluble and do not affect the osmotic potential of the water in the soil.

This, combined with the relatively low EC values—especially for drainage waters—suggests that in certain cases, this water could be reused for irrigation, with appropriate irrigation management. However, in the case of AB6, we observed higher SAR values (6.9) accompanied by slightly higher EC values (4.6 dS·m^{-1}). Reusing the drainage water from outlet AB6 for irrigation would lead to further complications. The nature of the dissolved ions would cause issues related to the effects of sodium on both soil and plants. This highlights the importance of knowing about the soil and geological material in a given area. We could putatively observe striking differences between sub-basins receiving waters of the same irrigation quality.

TABLE 3 | Comparison between drainage water quality in the sub-basin AB2 for the years of the study of Villar et al. (2015) and the present study. Values of electrical conductivity (EC) in dS. m^{-1}, values of ion concentration in mmol$_c$. L^{-1}. Average values ± standard deviation.

	2006–08	2021–2023
CE	4.9 ± 0.8	3.7 ± 0.9
Ca^{2+}	24.5 ± 3.7	25.3 ± 5.5
Na^{+}	14.6 ± 4.4	10.9 ± 3
Mg^{2+}	28 ± 5.9	18.8 ± 4.9
SAR	2.8 ± 0.7	2.3 ± 0.5

These data were compared to a previous study conducted in the area between 2006 and 2008 by Villar et al. (2015). They monitored outlets AB1 and AB2 when the irrigated area had been newly stablished (and covered 4,700 ha in the AB district compared to the present 7,000 ha). In **Table 3** we present some of the water quality results obtained in their study, and compared with the present one for sub-basin AB2. In **Table 3** we can observe a reduction in CE and in SAR values, accompanied with a reduction of concentration in Na^{+} and Mg^{2+} ions. However, Ca^{2+} concentration remains stable. Similar patterns were observed for AB1. This suggests that the application of high-quality irrigation water over the past 15 years has resulted in the leaching of salts and the improvement of soils in the area.

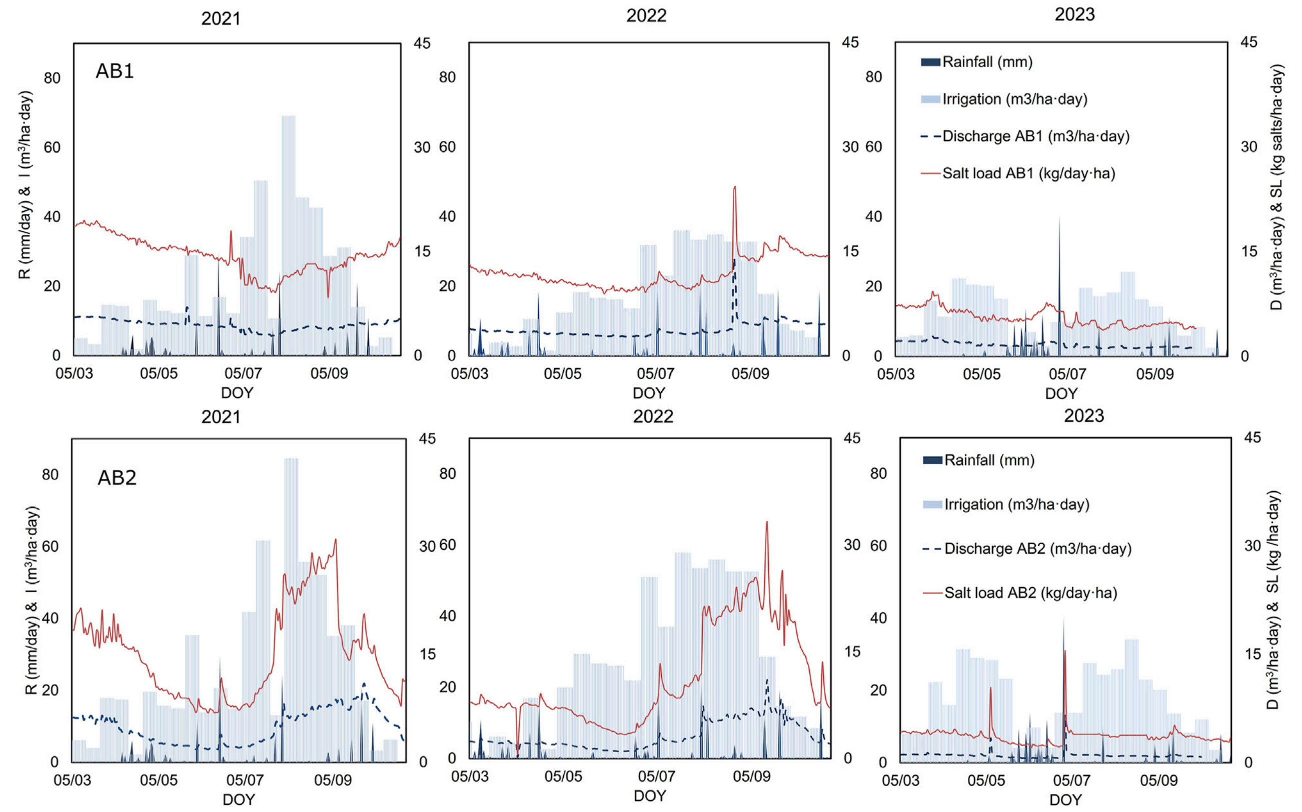

FIGURE 6 | Daily dynamics of irrigation (I), rainfall (R) drainage discharge (D) and salt loads (SL) for the two outlets studied (AB1, AB2) during the three study periods.

Drainage Volumes and Salt Balances

Figure 6 illustrates the daily dynamics of irrigation water inputs, drainage water amounts, and the estimated salt export from the irrigable area in the two studied sub-basins (AB1 and AB2). In 2021 and 2022, the impact of irrigation on the quantity of drainage water and the salts exported is clearly evident. As expected for the type of crops in the area, the majority of the irrigation water was used during the summer months, with average values ranging from 50 to 80 $m^3 \cdot ha^{-1} \cdot day^{-1}$. These high irrigation inputs led to an increase in drainage flow during these months; this was particularly evident at the AB2 outlet.

A delay was observed between irrigation application and drainage discharge. Despite the highest irrigation water usage occurring in July and August, peak drainage and salt discharge were recorded in September. This suggests that at the onset of the "second" irrigation period for maize, the soil was initially dry, resulting in minimal drainage. Over time, as the soil moisture increased, excessive drainage occurred from July to September, aligning with the period of peak irrigation demand. This indicates that irrigation management may have been less effective during periods of high irrigation demand compared to periods of lower demand.

Regarding the response to precipitation events, it was observed (dark blue bars in **Figure 6**) that the influence in AB1 was much smaller than in AB2, with the former having a significantly larger drainage basin (2587 ha vs. 114 ha). In AB2, there was a clear increase in the salt load in the days leading up to a rainfall event. In AB2, salt load values ranged from 20 to 30 $kg\ salt \cdot ha^{-1} \cdot day^{-1}$, while in AB1, it was lower, at 15 $kg \cdot ha^{-1} \cdot day^{-1}$. These values were consistent with those reported in other earlier salt balance studies conducted in the River Ebro basin (Abrahao et al., 2011; Andrés et al., 2020; Causapé et al., 2004a; García-Garizábal et al., 2009; Isidoro et al., 2006; Merchán et al., 2013; 2018).

The main differences between these studies were related to the geological and soil types, and also to the irrigation types (surface or sprinkler). This complicates the comparison of results across basins beyond salt exports and highlights the importance of studying each irrigated area individually. It also underscores the potential for improvements in water management and their overall impact.

In 2023, there was a noticeable decrease in irrigation water application compared to 2021: by 40% in AB1 and by 32% in AB2. The reduction in irrigation water application was mandated by the basin administrator (*Confederación Hidrográfica del Ebro, CHE*) in response to the hydrological drought experienced in the basin in 2023 Confederación Hidrográfica del Ebro (2024). Water availability for irrigation across the entire irrigable area was reduced to 75% compared to a normal year. However, through optimized water management at the irrigation district level, the actual irrigation water applied amounted to 70% of the amount applied in the previous 2 years (personal communication, 2023).

TABLE 4 | Irrigation (I, $m^3 \cdot ha^{-1}$), rainfall (R, $m^3 \cdot ha^{-1}$), salt input through irrigation (SI_I, $kg \cdot ha^{-1}$) and though rainfall (SI_R, $kg \cdot ha^{-1}$) and outputs as drainage volume (D, $m^3 \cdot ha^{-1}$) and drainage salt output (SO, $kg \cdot ha^{-1}$) during the three irrigation seasons studied in the two studied sub-basins.ΔSB and LF respectively accounted for the salt balance ($kg \cdot ha^{-1}$) and leaching fraction (%) associated with each case.

		Inputs				***Outputs***		***ΔSB***	***LF***
		I	***R***	***SI_I***	***SI_R***	***D***	***SO***	**(*kg/ha*)**	(%)
2021	AB1	4,843	1880	1,438	78	1,044	3,415	−1899	15.6
	AB2	5,920	1880	1758	78	1,158	3,558	−1722	14.8
2022	AB1	4,143	2,300	1,230	95	1,098	3,518	−2,193	17
	AB2	6,641	2,300	1972	95	882	3,063	−996	9.8
2023	AB1	2,878	1810	855	75	352	1,194	−264	7.5
	AB2	4,054	1810	1,204	75	233	865	414	3.9

We observed the effects of reduced irrigation water availability in both sub-basins. As shown in **Figure 6**, peak irrigation application occurred during the summer months in 2021 and 2022 but this level was not reached in 2023. In that year, maximum average daily irrigation inputs did not exceed 40 $m^3 \cdot ha^{-1}$. This shift could primarily be attributed to changes in irrigation management and land use by farmers. They relied more on irrigation for barley and left some acreage fallow, without sowing maize. This change in behavior led to decreased crop yields. However, the reduction in irrigation also led to a 66% reduction in drainage in AB1 and a 79% reduction in AB2, compared to 2021.

Moreover, during the first irrigation period application in 2023 (spring months), which corresponded to the winter cereal cycle, we observed a lower drainage discharge despite a higher water input through irrigation compared to 2021 and 2022, as seen in **Figure 6**. This suggests that when restrictions were imposed in the irrigation district, farmers improved their water management, possibly due to greater concerns about water usage.

An increase in irrigation during the spring months did not result in any corresponding increase in drainage during these months. Furthermore, despite a greater irrigation input, we observed a reduction in the leaching fraction in AB2 in 2022. This decrease in drainage was attributed to higher reference evapotranspiration (ET_o) in that year, likely influenced by higher temperatures compared to 2021 or 2023. This led to higher crop evapotranspiration (ET_c) values and increased irrigation demand.

At the same time, the reduction observed in 2023 resulted in a lower LF, with the value approaching the optimal level (LR), with this being even lower in the case of AB2 (**Figure 6**). The LF decreased from 15.6% in AB1 and 14.8% in AB2, to 7.5% and 3.9%. These results suggest that most of the excess drainage occurred during the summer months, coinciding with peak irrigation activity.

In has been observed that the salt balances varied across the 3 years analyzed (**Table 4**), with the amount of irrigation water applied being the determining factor. During the periods of unrestricted irrigation in 2021 and 2022, the salt balance shows that salt outputs through drainage were consistently high, ranging between 996 $kg \cdot ha^{-1}$ and 2,193 $kg \cdot ha^{-1}$. Since these amounts are less than the salt supplied by irrigation water, it is conclusive that salts are leaching from soils in the area. In contrast, in 2023, with irrigation inputs below average, salt outputs were significantly reduced. The salt balance (the difference between salts added by irrigation and rainfall and those removed through drainage, as indicated in **Equation 1**) was slightly negative in AB1 and positive in AB2. This outcome appears to confirm the validity of the Rhoades model (1974) for leaching requirements, as the only negative balance occurred in 2023 in the AB2 sub-basin, where the leaching fraction (LF) was lower than the leaching requirement (LR).

It is important to note that the drainage measures discussed in this research are those registered exclusively during the irrigation periods of the three study years. Consequently, references to salt exports pertain specifically to those occurring within this time-frame. Although there is reduction in drainage water flow during the winter period, salt exports still occurred during this season; however, these are not reflected in this study.

Ion Balance Assessment

Individual assessments of the predominant ions were conducted for each irrigation period within the two sub-basins studied. **Figure 7** provides a synthesis of the acquired data. The figure indicates that salt is exported in excess in most cases, except for sub-basin AB2 in 2023, where salt is retained in the soil. Sulfate emerged as the primary ion exported in substantial quantities, averaging −1,200 kg. $ha^{-1} \cdot year^{-1}$, likely due to the prevalence of gypsum in the local soils. Additionally, the bicarbonate (HCO_3^-) supplied by irrigation water exceeded the amount exported by drainage, suggesting possible reactions with soil calcium to form carbonate precipitates (as per **Equation 5**). This process likely facilitated the sequestration of inorganic carbon.

Considering **Equation 5**, and based on an average annual increase of 416 $kg \cdot ha^{-1}$ of HCO_3^- in the soil, approximately 41 kg $C \cdot ha^{-1} \cdot year^{-1}$ would be sequestered in the form of inorganic carbon via carbonate precipitates.

$$Ca^{2+} + 2HCO_3^- \rightarrow CaCO_3 \downarrow + H_2O + CO_2 \uparrow \qquad (5)$$

As noted by Entry et al. (2004), irrigation can serve as a tool to augment the sequestration of carbon within the soil, working in conjunction with organic C sequestration. Furthermore, this mechanism provides a valuable means of enhancing carbon sequestration in semi-arid regions, where soil organic matter

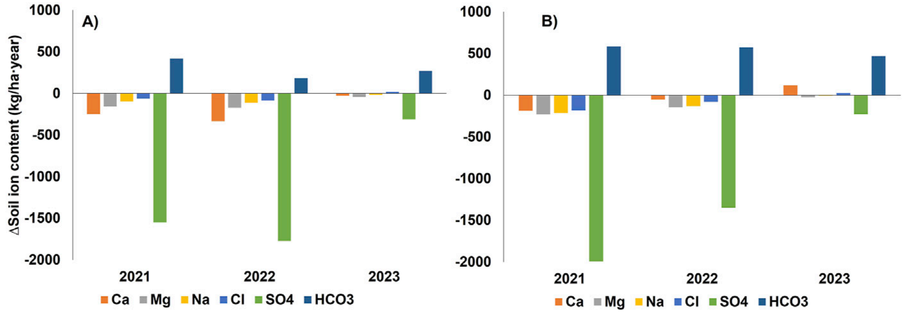

FIGURE 7 | Soil ion increase/decrease for each irrigation season in the two sub-basins studied, AB1 subfigure **(A)** and AB2 subfigure **(B)**. More detailed data are available in the **Supplementary Material**.

(SOM) is scarce and challenging to increase. This is particularly important in arid and semi-arid regions with low soil organic matter (SOM) levels.

Further research could focus on accounting the total amount of C sequestrated through irrigation in a certain irrigated area.

Future Recommendations

In view of the results obtained in the present study, some remedial measures can be carried out in the study area, which are described below.

From one side, an improvement in irrigation management is necessary to reduce the existing leaching fraction and reduce the downstream impact. As shown in **Table 4**, in years with normal irrigation (i.e. 2021-2022), leaching fractions between 9.8% and 17% were obtained during the irrigation period. This indicates that LF during the whole year exceeds these values, being five times higher than those necessary to maintain soil quality. To understand the excess LF in the study area, it is necessary to know the existing irrigation dynamics.

As indicated in **Table 1**, double crop (barley + maize) is the main land use in all the studied sub-basins, followed with alfalfa and maize (as in the whole studied irrigation district as well as in others irrigation districts in the Ebro basin).

Those crops are usually classified as summer crops, as its growing cycle occurs mainly during summer months. This fact, together with the reduced rainfall during this season, makes irrigation indispensable to obtain profitable productions.

At the same time, Salvador et al. (2011) observed that summer crops in the Ebro basin are usually over-irrigated. In sprinkler irrigation, they reported 20% and 25% higher irrigation water use with respect to the net irrigation requirement values in alfalfa and maize, respectively. This indicates an irrigation water use that may be leached on excess.

This results are similar to ones obtained in a previous study developed in the sub-basin AB5. Altés et al. (2023) found that maize and double crop fields were being over-irrigated between a 9%–12% with respect to the gross irrigation requirements, according to Allen et al. (1998).

One of the strategies to reduce LF is to adjust the irrigation depths to the irrigation requirements of the crops. As can be seen in **Figure 6**, September accounts for the highest drainage volume discharge. It is in this late period of the crop cycle when irrigation requirements begin to decrease. However, according to Altés et al. (2024), irrigation depths in the area are not reduced correspondingly, being responsible for this excess leaching.

On the other hand, water quality parameters indicate that three sub-basins drainage water can be easily reused (AB1, AB2, AB5). According to Ayers and Wescot (1985), these are medium-low quality water in therms of EC, but with low sodium content. This, combined with the use of good quality water (as is currently being used), can be a tool to reduce the total use of irrigation water diverted upstream, and in turn reduce the impact of the irrigable area downstream, without a reduction in the soil quality of the irrigable area. At the same time, it increases water resources downstream available for other users.

CONCLUSION

This study focused on monitoring drainage water quality in various sub-basins within a modern irrigation district located in the Ebro basin, northeastern Spain, over three consecutive irrigation periods. Our findings demonstrate distinct variations in drainage water quality among sites irrigated with identical water sources. This underscores the need to discern soil types at each site prior to evaluating potential water reuse and/or its leaching requirements. While drainage water in three of the sub-basins which were studied presented suitability for irrigation reuse without any significant issues, one site exhibited high levels of electrical conductivity and sodium adsorption ratios, pointing to its unsuitability. Analyses of salt balances over the study period also revealed a consistent trend of greater salt outputs than inputs, with drought years changing this dynamic due to insufficient water inputs for maintaining the minimum levels required for leaching. It is significant that in 2023, which was a year characterised by irrigation restrictions, salt accumulations occurred in the soil. In the case of ion concentrations, high sulfate levels in drainage water were primarily attributed to the abundance of gypsum in the soils in the study area. This altered the relationship between electrical conductivity and total dissolved ions. This study also suggest the significance of accounting for inorganic carbon accumulation in calcareous soils. This could be attributable to the precipitation of calcium carbonate resulting from irrigation involving bicarbonate-type water. Reducing irrigation doses at the end of the vegetative cycle might lower the leaching fraction reported in this study. Moreover, the reuse of the drainage water may promote sustainable water use in the region.

DATA AVAILABILITY STATEMENT

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

AUTHOR CONTRIBUTIONS

VA: conceptualisation, data curation, formal analysis, methodology, visualisation, writing–original draft. MP: formal analysis, supervision, writing–review and editing. JMV: funding acquisition, resources, supervision, methodology, writing–review and editing. All authors contributed to the article and approved the submitted version.

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CONFLICT OF INTEREST

Author VA was employed by isardSAT SL.

The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontierspartnerships.org/articles/10.3389/sjss.2024.13522/full#supplementary-material

REFERENCES

Abrahao, R., Causapé, J., García-Garizábal, I., and Merchán, D. (2011). Implementing Irrigation: Salt and Nitrate Exported From the Lerma Basin (Spain). *Agric. Water Manag.* 102, 105–112. doi:10.1016/j.agwat.2011.10.011

Agència Catalana de l'Aigua (2013). *Cartografia d'aqüífers de Catalunya*. Barcelona: Tech. rep., Agència Catalana de l'Aigua.

Allen, R. G., Pereira, L. S., Raes, D., and Smith, M. (1998). *Crop Evapotranspiration. Guidelines for Computing Crop Water Requirements. FAO Irrigation and Drainage Paper 56*. Rome: FAO.

Altés, V., Bellvert, J., Pascual, M., and Villar, J. M. (2023). Understanding Drainage Dynamics and Irrigation Management in a Semi-arid Mediterranean Basin. *WaterSwitzerl.* 15, 16–23. doi:10.3390/w15010016

Altés, V., Pascual, M., Escorihuela, M. J., and Villar, J. M. (2024). Assessing Irrigation Impact on Water Quality Conditions: A Case Study in the River Noguera Ribagorçana (NE Spain). *Agric. Water Manag.* 296, 108809. doi:10.1016/j.agwat.2024.108809

Andrés, R., and Cuchí, J. A. (2014). Salt and Nitrate Exports from the Sprinkler-Irrigated Malfarás Creek Watershed (Ebro River Valley, Spain) During 2010. *Environ. Earth Sci.* 72, 2667–2682. doi:10.1007/s12665-014-3174-0

Andrés, R., Martín-Ramos, P., and Cuchí, J. A. (2020). Water Balance and Nitrate and Salt Exports from a Saline–Sodic Irrigation District in Castelflorite (Huesca, NE Spain). *Agronomy* 10, 165 [pp. 16]. doi:10.3390/agronomy10020165

Ayers, R., and Wescot, D. (1985). *Water Quality for Agriculture*, 1. Rome: FAO Irrigation and Drainage Paper 29 Rev.

Barros, R., Isidoro, D., and Aragüés, R. (2015). Three Study Decades on Irrigation Performance and Salt Concentrations and Loads in the Irrigation Return Flows of La Violada Irrigation District (Spain). *Agric. Ecosyst. Environ.* 151, 44–52. doi:10.1016/j.agee.2012.02.003

Boixadera, J., Danés, R., and Porta, J. (1989). "Sistema d'informació de sòls de Catalunya (CatSIS)," in Comunicacions de la XVI Reunion de la Sociedad Española de la Cienca del Suelo *(Lleida)*.

Causapé, J., Quílez, D., and Aragüés, R. (2004a). Assessment of Irrigation and Environmental Quality at the Hydrological Basin Level: I. Irrigation Quality. *Agric. Water Manag.* 70, 195–209. doi:10.1016/J.AGWAT.2004.06.005

Causapé, J., Quílez, D., and Aragüés, R. (2004b). Assessment of Irrigation and Environmental Quality at the Hydrological Basin Level: II. Salt and Nitrate Loads in Irrigation Return Flows. *Agric. Water Manag.* 70, 211–228. doi:10.1016/j.agwat.2004.06.006

Confederación Hidrográfica del Ebro, M. P. L. T. E. (2024). Informe de la Sequía 2023 (Año Hidrológico 2022-2023). *Tech. Rep.*

Cox, C., Jin, L., Ganjegunte, G., Borrok, D., Lougheed, V., and Ma, L. (2018). Soil Quality Changes Due to Flood Irrigation in Agricultural Fields Along the Rio Grande in Western Texas. *Appl. Geochem.* 90, 87–100. doi:10.1016/j.apgeochem.2017.12.019

Departament d'Acció Climàtica, A. i. A. R. (2021). *Dun-Sigpac Crop Map*.

Doorenbos, J., and Pruitt, W. (1977). *Guidelines for Predicting Crop Water Requirements*. Rome: FAO Irrigation and Drainage. *Paper* 24.

Entry, J. A., Sojka, R. E., and Shewmaker, G. E. (2004). Irrigation Increases Inorganic Carbon in Agricultural Soils. *Environ. Manag.* 33. doi:10.1007/s00267-003-9140-3

FAO (2002). *Crops and Drops: Making the Best Use of Water for Agriculture*. Rome: Tech. rep., FAO.

Fereres, E., Orgaz, F., and Gonzalez-Dugo, V. (2011). Reflections on Food Security under Water Scarcity. *J. Exp. Bot.* 62, 4079–4086. doi:10.1093/jxb/err165

García-Garizábal, I., Abrahao, R., and Causapé, J. (2012). El Manejo del Riego y la Contaminación por Sales y Nitrato: Un Caso De Inundación Vs. Aspersión. *Inf. TÉCNICA ECONÓMICA Agrar.* 108, 482–500.

García-Garizábal, I., Valenzuela, J. C., and Abrahão, R. (2009). Evolution of the Efficiency and Agro-Environmental Impact of a Traditional Irrigation Land in the Middle Ebro Valley (2001–2007). *Span. J. ofAgricultural Res.* 7, 465–473. doi:10.5424/sjar/2009072-1499

Gil, C., Santos, J., and Esnaola, J. (1998). *Mapa Geológico y Memoria de la Hoja no 359 (Balaguer). Mapa Geológico de España E. 1:50.000*. Madrid: Tech. rep., Instituto Tecnológico Geominero de España.

Hart, B. (1974). *A Compilation of Australian Water Quality Criteria. (Australian Water Resources Council Techn Paper Nr 7)*. Canberra: Tech. rep., Australian Government Publishing Service.

Hillel, D., Braimoh, A. K., and Vlek, P. L. (2008). "Soil Degradation under Irrigation," in *Land Use and Soil Resources*. Editors V. P. Braimoh and A. K. Dordrecht doi:10.1007/978-1-4020-6778-5{_}6

Instituto Geológico y Minero de España and Dirección General del Agua (2010). *Identificación y caracterización de la interrelación que se presenta entre aguas subterráneas, cursos fluviales, descargas por manantiales, zonas húmedas y otros ecosistemas naturales de especial interés hídrico. 091.061 Aluvial del Bajo Segre*. Madrid: Tech. rep., Instituto Geológico y Minero de España, Ministerio de Ciencia e Innovación, Gobierno de España.

Isidoro, D., Quílez, D., and Aragüés, R. (2006). Environmental Impact of Irrigation in La Violada District (Spain). *J. Environ. Qual.* 35, 766–775. doi:10.2134/jeq2005.0064

Institut Cartogràfic i Geològic de Catalunya (2019). *Balaguer 359-2-1 (64-27) Soil Map 1:25.000*.

Institut Cartogràfic i Geològic de Catalunya (2020). *Digital Elevation Model 2x2*.

Jiménez-Aguirre, M. T., and Isidoro, D. (2018). Hydrosaline Balance in and Nitrogen Loads from an Irrigation District before and after Modernization. *Agric. Water Manag.* 208, 163–175. doi:10.1016/j.agwat.2018.06.008

McNeil, V. H., and Cox, M. E. (2000). Relationship between Conductivity and Analysed Composition in a Large Set of Natural Surface-Water Samples, Queensland, Australia. *Environ. Geol.* 39, 1325–1333. doi:10.1007/s002549900033

Mensua, S., Fernández, S., Ibáñez, M., Marcellán, M., Yetano, M., and Ruiz, M. (1977). *Sector Central de la Depresión del Ebro, Mapa de terrazas fluviales y glacis*. 1st ed. Zaragoza: Universidad de Zaragoza, Departamento de Geografía.

Merchán, D., Casalí, J., Del Valle de Lersundi, J., Campo-Bescós, M. A., Giménez, R., Preciado, B., et al. (2018). Runoff, Nutrients, Sediment and Salt Yields in an Irrigated Watershed in Southern Navarre (Spain). *Agric. Water Manag.* 195, 120–132. doi:10.1016/j.agwat.2017.10.004

Merchán, D., Causapé, J., and Abrahão, R. (2013). Impact of Irrigation Implementation on Hydrology and Water Quality in a Small Agricultural Basin in Spain. *Hydrological Sci. J. – J. des Sci. Hydrologiques* 58, 1400–1413. doi:10.1080/02626667.2013.829576

Ministerio para la Transición Ecológica y el Reto Demográfico (2022). *Caracterización adicional de las masas de agua subterránea MSBT: ES091MSBT061 - Aluvial del Bajo Segre*. Tech. rep., Ministerio para la Transición Ecológica y el Reto Demográfico.

Murray, R., and Grant, C. (2007). Impact Of Irrigation On Soil Structure. *Tech. Rep.* Canberra: Australian Government, Land and Water Australia.

Olivera-Guerra, L.-E. E., Laluet, P., Altés, V., Ollivier, C., Pageot, Y., Paolini, G., et al. (2023). Modeling Actual Water Use under Different Irrigation Regimes at District Scale: Application to the FAO-56 Dual Crop Coefficient Method. *Agric. Water Manag.* 278, 108119. doi:10.1016/j.agwat.2022.108119

Piper, A. (1944). A Graphic Procedure in the Geochemical Interpretation of Water-Analyses. *os, Trans. Am. Geophys. Union* 25, 914–928. doi:10.1029/TR025i006p00914

Quílez, D. (1985). *Descripción, análisis y aplicación de un modelo hidrosalino del sistema flujos de retorno de riego. Bachelor thesis. Tech. rep.* Zaragoza: Universidad de Zaragoza.

Rhoades, J. (1974). "Drainage for Salinity Control," in *Drainage for Agriculture*, 433–468. J. van Schilfgaarde (Agronomy Monographs). doi:10.2134/agronmonogr17.c21

Rhoades, J., Chanduvi, F., and Lesch, S. (1999). *Soil Salinity Assessment. Methods and Interpretation Fo Electrical Conductivity Measurements*. Rome: FAO Irrigation Drainage Paper.

RuralCat Departament d'Acció Climàtica Alimentació i Agenda Rural (2023). *Dades Agrometeorològiques*

Rusydi, A. F. (2018). Correlation between Conductivity and Total Dissolved Solid in Various Type of Water: A Review. *IOP Conf. Ser. Earth Environ. Sci.* 118, 012019. doi:10.1088/1755-1315/118/1/012019

Salvador, R., Martínez-Cob, A., Cavero, J., and Playán, E. (2011). Seasonal On-Farm Irrigation Performance in the Ebro Basin (Spain): Crops and Irrigation Systems. *Agric. Water Manag.* 98, 577–587. doi:10.1016/J.AGWAT.2010.10.003

Soil Survey Staff (2022). Keys To Soil Taxonomy *(USDA Natural Resources Conservation Service)*. 13th ed.

Stosch, H.-G. (2022). *Excel Template to Plot Hydrochemical Data into a Piper Diagram (1.0)*. doi:10.5281/zenodo.5994293

Tedeschi, A., Beltrán, A., and Aragüés, R. (2001). Irrigation Management and Hydrosalinity Balance in a Semi-arid Area of the Middle Ebro River Basin (Spain). *Agric. Water Manag.* 49, 31–50. doi:10.1016/S0378-3774(00)00117-7

USSL (1954). *Diagnosis and Improvement of Saline and Alkali Soil*. USDA Agric. Handbook 60.

Villar, J., Pascual, M., Rufat, J., and Villar, P. (2015). El impacto del riego en la calidad del agua de drenaje en una nueva zona regable. *Ing. del agua* 19, 241–253. doi:10.4995/ia.2015.4113

Wang, L., and Liu, H. (2006). An Efficient Method for Identifying and Filling Surface Depressions in Digital Elevation Models for Hydrologic Analysis and Modelling. *Int. J. Geogr. Inf. Sci.* 20, 193–213. doi:10.1080/13658810500433453

ORIGINAL RESEARCH
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Values Are Not Taught, Values Are Built

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Forming values to contribute to the complete formation of the human being as responsible citizens is an educational task that is indispensable to the construction of sustainability. Consequently, this document states that achieving a construction of values that leads to true development is not possible without a teaching and learning of science that, starting from an intersystemic and therefore complex vision of the world, allows us to build them. Answering the question How can interdisciplinary science teaching contribute to generating in today's children a genuine interest in the study and knowledge of science in general, and in the conservation of natural resources in particular? Was the objective of the methodological proposal for interdisciplinary science teaching that was previously described in the article "Teaching soil science: a strategy and warranty towards the future" (Reyes-Sánchez, 2012). This second document addresses why, how and for what purpose the formation of values and principles accompanied this methodological proposal for interdisciplinary science teaching as a qualitative pedagogical approach that was applied within two schools with children in 5th and 6th grade of basic education –10 and 11 years of age-: by amalgamating the construction of knowledge with that of values to support the appropriation of both in a playful way, seeking and encouraging in children the congruence between knowledge, thought and action. The differences in children's opinions regarding life problems that affect the social, political and economic order before and after the pedagogical intervention are presented in a comparative manner.

Keywords: education, interdisciplinary teaching, values, social responsibility, sustainability

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INTRODUCTION

When UNESCO defined Environmental Education in 1971, it made clear its intrinsic relationship with the construction of environmental awareness and culture, defining it as the "process that consists of recognizing values and clarifying concepts in order to foster the attitudes necessary to understand and appreciate the interrelations between man, his culture and his biophysical environment." In this regard, while it is true that the increase in urbanization of society and its detachment from the food production process means that a significant proportion of the human population lacks a fundamental understanding of what the natural resource soil. An important part of the population do not know what the soil means to society, its functions, the benefits received from it and, where their food comes from. It is also true that if we want to build citizen awareness about the value of soil resources, then we must understand that this is the result of a complex process that begins with our lives within the family and the environment that surrounds us but is forged at school and each teacher leaves a mark on its formation. Therefore, understanding the difference between teaching and educating in order to raise awareness, is of vital importance when it comes to preserving natural resources.

This document presents both the activities that were planned and carried out in this qualitative exploration to address the formation of values that accompanied the construction of knowledge in a playful way. With this in mind, the document also shows the comparative differences that children in the penultimate year of basic education from two different schools (work groups) expressed regarding different values, compared to those expressed by those same children after being pedagogically intervened throughout the school year.

The differences expressed for the same values are contrasted with children for the intact groups from two different schools.

PROPOSAL

Why Teach Soil Science Simultaneously Addressing the Construction of Values?

Science, constituted as a collective and organized body that develops scientific knowledge, is very recent in the context of human history, and over the last centuries the concept and model of science has changed in response to new knowledge, becoming a qualitative and quantitative dialectical construction of the same (Bernal, 1979). The dialectical construction of science as a product of human actions and activities of cognitive construction is transmitted through the educational system; it is therefore educated through teaching and taught at school; this means that, what is taught at school is school science (Reyes-Sánchez, 2012). Science and the teaching of science, which throughout human history has been influenced by the different dominant forms of thought in each era, and in a systematic, conscious and planned way has been and is the educational tool through which; although it seeks to efficiently and effectively transmit the experiences and information accumulated on knowledge, it is also true that through what is taught in the school educational system, it is sought to reproduce a certain culture and finally, the power inherent to that culture. But teaching *is not educating*. Teaching is only a part of educating, but not the same. Educating necessarily involves the explicit and implicit formation of values that emotionally and cognitively root the scientific information transmitted, thus making possible the *progressive formation* of a conscience that in the medium and long term builds, little by little, a culture of preservation (*Ibid.*). *Teaching is only one part of the educational process, since teaching is not the same as learning, and learning is not the same as learning meaningfully.*

Teaching, as an educational learning process, necessarily requires manifesting itself in an integral way, revealing itself through the individual and collective habits and attitudes that have been learned. If learning is not meaningful, then only part of the teaching process was carried out; there is therefore no appropriation[1] of knowledge -significant learning-, since it cannot be expressed or reflected in the daily actions of the citizen (Morales et al., 2011). That is why, in contrast to traditional memoristic education whose social purpose seeks to affirm tradition, the established order and conservatism, for the new school of Celestine Freinet (1949), active education is the full development and elevation of the spirit, not the accumulation of knowledge or domestication, nor the conditioning of the child.

Education and teaching are for Unamuno, "the very action of humanly edifying youth, of making them men, through the search for truth and the passion for it, knowledge and the struggle with oneself; of the spiritual awakening and material prosperity of a country and the mystery surrounding the final destiny of man and his world" (Robert, 1985). From the pedagogical perspective of Anton Makarenko (1959), education must harmonize social interests with the particular interests of students, involving them in the search for solutions to everyday problems. While education, as conceived today by the Freinet Modern School of Pedagogy movement (Legrand, 1993), aims to contribute to the complete formation of the human being through the provision of *knowledges*, *abilities*, *skills*, *values*, *attitudes*, *beliefs* and *ways of acting*.

According to Echeverría (1995), scientific activity is developed in four areas: innovation or discovery, evaluation or justification, teaching and application; and it is precisely in teaching where normative scientific knowledge is consolidated, which each generation considers essential in order for that young people to be able to join a disciplinary group.

That is why, school, being normative and precisely because school is, is also a context of scientific activity.

And What Is Proposed?

Gómez et al (2004), argue that when talking about education, it is necessary to understand that educating for sustainability is an objective that goes beyond a subject, or set of subjects in the curriculum. That it is not about reproducing forms centered on technique, but about teaching science inviting in unison to debate and reflection on the type of technology and social organization that allow people to live in harmony with each other and the natural environment.

All of these conceptualizations and approaches not only allow us to approach from the classroom, the concept of environmental education of UNESCO (1987), as a "permanent process in which individuals and communities become aware of their environment and acquire the knowledge, *values*, skills, experience and will that will allow them to act, individually and collectively, to solve current and future environmental problems;" but they support it and add to the founding premises of the (Belgrade, 1975): raising awareness, acquiring basic knowledge, cultivating attitudes, acquiring skills, fostering critical capacity and promoting citizen participation, to propose *how to build, through teaching, that education that, while fulfilling the objectives described, serves the purpose of educating for development.*

Accordingly, the pedagogical proposal worked on also coincides with the OEI (1995), when it states that values are not innate, they are constructed and therefore, we can consider them as ideals to be achieved, which represent challenges to overcome in everyday life: in each activity we carry out and each

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[1] Methodological cognitive process through which the individual manages to make knowledge his own in such a way that he reorganizes it, transforms it, builds new links with practice, and adapts it to the contexts of action and application; in short, he achieves an understanding of concepts of greater complexity (Reyes-Sánchez, 2009).

relationship we establish. Consequently, the need for a change of perspective on how to teach science is assumed and that this is done in the classroom through activities and reflections on the models of action and consumption that allow us to think about assuming new social models of behavior, because pollution, devastation, degradation and loss of natural resources are not problems that can be solved scientifically and technologically with the current predominant values, based on competition, lack of solidarity, uniformity or hierarchization, governed by the market (Novo, 1995; Gutiérrez, 1995; Pardo, 1995; García et al., 2000; Gómez et al., 2004), and fully assumes that the effort of daily work generates added value in terms of training and appropriation.

MATERIALS AND METHODS

The methodological position adopted in relation to the object of study was qualitative for exploratory and interpretive purposes; the sample was made up of intact groups to which a pre-test and post-test were applied to evaluate the expected changes for interpretive purposes. The aim was to start with school groups that were as similar as possible in terms of the variables relevant to the study: age, school year, socioeconomic status, nationality, geographic school and residential area at the municipal level, and sex. Regarding the latter condition, all groups were mixed.

The method was the environmentalization[2] of the knowledge that the children had regarding the soil resource combined with the formulation of moral dilemmas that confronted their values and knowledge through group and individual reflection on the social and economic problems that were directly or indirectly associated with the soil. To do this, the aim of this experience was to conflict their positions through the presentation, argued and propositional discussion of alternatives that represented their personal positions to the moral dilemmas that were presented to them. Personal positions that, when questioned or reinforced by their classmates in the classroom and the moderating intervention of the teacher, could offer normative capacity in the short and long term in the construction of values and principles within the school.

For this purpose, a whole range and sequential program of sessions, content, activities and experiments, discussions, games, exhibitions, events, etc., was developed, which would provide an environment for knowledge of the soil system by interrelating it to the environment system with which it maintains complex intersystemic relationships; always seeking to integrate the various disciplines of the school curriculum with respect to their social, economic, political and cultural perspectives, and at the same time to conflict their knowledge through moral dilemmas assumed from those same perspectives.

The application of the proposal was carried out through direct pedagogical intervention to intact groups in two schools in Cuautitlán Izcalli, Mexico, and the evaluation instruments were subjected to both frontal validity and expert judgment. The proposal was applied to the entire sample when the children were in the 5th year of basic education and the post-test was applied when the children finished the 6th year of basic education (8 months later), with the objective that their responses corresponded to a long-term appropriation (Ausubel, 1973).

> *"Liven up teaching with the beautiful word, with the appropriate anecdote, and the relationship of each knowledge with life"*
>
> Gabriela Mistral.

The hypothesis underlying this proposal is that it is possible to promote a normative action based on a constructive teaching of science. To achieve that the aim was to simultaneously address both the interdisciplinary knowledge of the soil system and the normative perspective of that knowledge. For this purpose, discussion and work dynamics were developed that would lead to reflection and encourage in children the formation of values, principles and attitudes related to the construction of sustainable development.

It is exemplified by the three phases of a moral dilemma worked on during this pedagogical intervention and the arguments offered to the children to develop this experience are described.

The Limits of Growth That Nature Imposes

Assuming the existence of the limits of growth that nature imposes on us (Meadows, 1977), orienting knowledge, values and behaviors towards sustainable patterns for consumption and management of resources as a necessity in the construction of development was one of the topics considered essential. Regarding how to bring the topic to the classroom through a didactic transposition that contemplated interdisciplinary integration from various fields of knowledge, it was proposed to carry out a set of activities to be carried out during three consecutive work sessions (for 3 weeks). The subjects of the basic curriculum that were sought to be incorporated were mathematics, history, geography, natural sciences and their social connection.

The objectives to be incorporated in relation to knowledge of the soil resource for discussion with the children were: a) Understand that not all soils are fertile for food production, b) Understand that the surface of fertile soil is small, and it can be easily lost and c) Promote the formation of a critical and respectful awareness of the environment.

How Much Soil do We Have to Produce Our Food?

The children participate in the discussion and calculate on each occasion the fractions that occupy water and land in the planet, as well as each of the fractions corresponding to the different areas covered by soil, while the teacher begins the following conversation with the pedagogical intention of appropriating knowledge and reflecting on the value of the soil resource and what its loss means.

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[2] A methodological process that approaches the environmental problems in a cognitive and interdisciplinary way through education and the practice of science with the objective of building a preservation culture and conscience by providing models for the management and exploitation of natural resources towards the development for all (Reyes-Sánchez, 2009).

Approach: Knowing that ¾ parts of Planet Earth are water and only ¼ is made up of solid land, the students are shown graphically using an apple or an orange as a model, what real fraction is the one that makes up the areas in which we live and what its fragility is (the apple is cut and the only quarter that corresponds to solid land is shown to them). Of the remaining fraction: ¼, not all of it is habitable, large extensions make up deserts, mangroves, rocky soils and high mountain soils where we cannot plant due to their steep slopes, and where, on the contrary, if the soil does not have a vegetal cover, the water drags that soil that is thus lost from those areas, eroding them. This means that only approximately half of the quarter that constitutes the solid plates is habitable for man, (the children are asked to do the mathematical calculation) that is, 1/8 of the total of the Planet.

Part of this eighth fraction is occupied by large and small cities that therefore cover the soil with concrete, which makes that soil no longer cultivable. On the other hand, if we think that the eighth part of the Planet that is habitable, it is divided into at least another four, then.

- 1/32 would be covered by concrete by the large and small cities where we live and the roads that connect them.
- 1/32 is made up of areas with slopes too steep to be used for the production of our food.
- 1/32 has very poor soils and therefore cannot be used for agricultural production. How much fertile soil would we have left? (The apple is cut graphically showing all the fractions).

Only 1/32 of the solid plate would be covered by fertile soil and therefore could be cultivated, only 1/32!

On the other hand, the world population has grown so much and is so disrespectful of the environment that it does not always properly use that eighth part of the Earth that is more habitable; Thus, for example, in the area where we live, over the last 50 years, the fertile soils of the Cuautitlán Valley have been covered each year in greater proportion by the asphalt layer that now covers the City of Cuautitlán Izcalli. This has also changed the economic activities of its original inhabitants and made their lives more expensive as the city and its population grow, given that now, families have to buy fruits and vegetables that are brought from far away, and that were previously produced in the surrounding area. Those who owned those lands, by selling their land to the construction companies, were left without fertile land on which to work and now have to look for work that is mostly found in Mexico City, which means they have to move. To do so, they spend 3 or 4 h/day that steal from their sleep and from their family, they get more tired, they use transportation that is expensive and that pollutes the air we breathe.

Reflection: Are we adequately planning our future life on Earth?

Task: Search the school library and/or the Web for information about how long it takes for soil to form.

How Is the Earth Made Up?

For this second part, we will go back to what we have done in the previous class, using an apple or an orange as didactic models that represent The Earth.

Children explain how the Earth is made up, what its different layers are, what is in its core, etc. The last layer of the planet, that is, the lithosphere, contains the soil that has been formed over millions of years, and only 1/32 of this lithosphere is covered by fertile soil. What is the size of this layer of soil that covers the lithosphere? The layer of soil that covers the lithosphere is as thin as the shell of our educational model: extremely thin and therefore fragile! Very easy to lose.

On the last layer of the planet - that is, on the lithosphere - is deposited the soil that has been formed over millions of years, and only 1/32 of this lithosphere is covered by fertile soil. What is the dimension of this layer of soil that covers the lithosphere? The layer of soil that covers the lithosphere is as thin as the shell of our educational model: extremely thin and therefore fragile! Very easy to lose.

Only about 1/32 of the habitable part of the planet has fertile soil, and the life of all living beings on the planet depends on the existence of this fertile soil to produce their food. However, we continue to cover part of this fertile soil with asphalt to accommodate an ever-growing population; We are losing another part of this fertile soil, because when we deforest, the water and air take with them the fertile soil that we need to produce our food. We also contaminate it with large quantities of agrochemicals and accelerate its degradation.

Activity: Search for information to answer the following questions: How many tons of fertile soil are lost per year in Mexico and in the world? How many hectares of vegetation are lost per year and for what reasons?

Reflection: Let us think again about our previous activities, discussions and conclusions: Are we, the inhabitants of the Earth, planning our lives adequately?

Homework: Search in the school library and/or on the Web for information about the time it takes for soil to form.

How Long Does it Take for Soil to Form?

The books say that, on average, 1 cm of soil is formed in 300 years. No man can live to wait for the 30 cm required to plant our vegetables to form!

During this session, we will work on how soil was formed through the action of weathering agents and from the environment on the Earth's crust (weathering), and what factors intervened in this.

Experiment: To understand the action of these agents on the Earth's crust, we will carry out a didactic experiment using three eggs as a model; each one is immersed in a glass filled halfway with: plain water in one, vinegar and lemon juice in the other two. What happens to the eggshells of eggs immersed in these three different media over time if we observe them for 5 days in a row? The observations are discussed in class.

Activity: Let us suppose that each centimeter of fertile soil that is lost took at least 300 years to form; if to grow the vegetables that you have on your school plot we need 30 cm of fertile soil, how many years did it take to form those 30 cm on which we grow today at your school?

Reflection: If we are all part of the same food chain, will we be able to survive as a species if we continue to lose fertile soil? Will

TABLE 1 | Pre and post-concepts of children from the “Professor Alfonso Sánchez García” Institute and the “Leyes de Reforma” School.

Values and attitudes		Institute Sánchez García	Inst. Sánchez García	Leyes de Reforma school	Leyes de Reforma school
		Final	Initial	Final	Initial
		6° (18)	5° (19)	6° (15)	5° (13)
Problem 1	Rosa’s grandmother has been sick for several months and sometimes the family cannot go out for walks because they have to stay home to take care of her	% of answers	% of answers	% of answers	% of answers
The reasonable thing would be to put her in a nursing home		5.55	0	0	7.69
Family should come to an agreement with other relatives to take turns caring for her		50.00	10.52	60.00	30.76
We all have to look after the elderly, because they looked after us and fed us when we were children		0	0	40.00	61.53
Grandparents should be self-sufficient and see how they can manage on their own		44.44	89.47	0	0
Problem 2	At most bus stops, benches with roofs were placed so that passengers could wait comfortably, without getting sunburned or wet; however, the vast majority of them were destroyed by the young people of the city	11.11% did not answer	26.31% did not answer	All answered	All answered
They are right to destroy them, because that is how they express their discontent with the conditions in which they live		0	5.26	6.66	38.46
That is not the way to solve or express themselves about the problems that exist, nor does it contribute to improving the living conditions of the community		88.88	68.42	60.00	30.76
Those who do so should be imprisoned		0	0	26.66	30.76
That does not affect me		0	0	6.66	0

any species be able to wait for the next 30 cm of soil to form? We will share everyone’s opinions in the next class.

REMARKS

In this work, although the aim was to encourage children to have congruence between knowledge, thoughts and actions, the different responses were not evaluated in order to assign them any kind of grade. On the contrary, it was considered that respect for the diversity of thought regarding the knowledge of individuals is an element of life and not of repetition or memory. Their opinions regarding life problems that affect the social, political and economic order in relation to the land resource before and after the intervention are presented in a comparative way.

Tables 1–4 present the differences in the values that the children assumed in the face of the moral dilemmas posed in order to detect signs of change in their values after the pedagogical intervention, not generating value judgments in this regard but looking for signs of change in their values with respect to those they have been expressed in writing before the intervention.

Under the hypothetical assumption that it is possible to promote a normative action from a constructive teaching of science, after having worked on the cognitive part and addressing the normative through the presentation of moral dilemmas, search for information, brainstorming, collective discussions and homework, the analysis of the children’s reflections that correspond to their answers, generally reveals some change in the direction indicated below for each of the problems raised:

1. Greater equity in the distribution of tasks at the family level on how to care for the elderly.
2. More reasonable and less aggressive positions in the face of current violence.
3. Greater commitment and involvement in the face of pollution problems.
4. They seek to be equitable without achieving it when they assume that water should be rationed equally for everyone, because in reality that is inequitable, and the real way to be fair in this regard would be charging more to those who have more and spend more.
5. Greater recognition of the value of the soil resource, based on the differentiation of its use.
6. They failed to understand the real meaning of the loss of agricultural soil for their lives.
7. They are seeking more equitable measures.
8. There has been progress in understanding the problems of the countryside and the lack of government support for farmers is clear to them.

TABLE 2 | Pre and post-concepts of children from the "Professor Alfonso Sánchez García" Institute and the "Leyes de Reforma" School.

Values and attitudes		**Institute Sánchez García**	**Inst. Sánchez García**	**Leyes de Reforma school**	**Leyes de Reforma school**
		Final	**Initial**	**Final**	**Initial**
		6° (18)	**5° (19)**	**6° (15)**	**5° (13)**
Problem 3	Water in Mexico's lakes and rivers is dirty and contaminated	16.66% did not answer	All answered	All answered	All answered
This is everyone's responsibility		11.11%	31.57%	40.00%	46.15%
The responsibility lies with the companies that pollute it		0	15.78%	13.33%	23.07%
The responsibility lies with the government that does not enforce the rules		0	0	13.33	23.07
We all need to take responsibility for this and take real action to conserve it		72.22%	56.63%	33.33%	7.69%
Problem 4	There is not enough water in urban areas to cover the total demand of the population, which is why	16.66% did not answer	10.52% did not answer	All answered	7.69% did not answer
Water should be rationed equally for everyone		66.66%	52.63%	66.66%	53.84%
Water should be given only to those who can afford it		0	5.26%	0	7.69%
More should be charged to those who can afford it, but everyone should have access to it		16.66%	5.26%	6.66%	15.38%
Its price should be raised so that people do not waste it, even if not everyone can afford it		0	26.31%	26.66%	15.38%
Problem 5	The soil resource	16.66% did not answer	5.26% did not answer	All answered	All answered
It is the same everywhere in the world		11.11%	21.05%	26.66%	7.69%
It can be used for any activity		5.55%	10.52%	6.66%	46.15%
It is not indispensable for human life		5.55%	5.26%	6.66%	7.69%
Soils useful for agriculture should be more valuable than others and should be preserved for that purpose		61.11%	57.89%	60.00%	38.46%

TABLE 3 | Pre and post-concepts of children from the "Professor Alfonso Sánchez García" Institute and the "Leyes de Reforma" School.

Values and attitudes		**Institute Sánchez-García**	**Inst. Sánchez García**	**Leyes de Reforma school**	**Leyes de Reforma school**
		Final	**Initial**	**Final**	**Initial**
		6° (18)	**5° (19)**	**6° (15)**	**5° (13)**
Problem 6	The loss of fertile soil for agricultura	16.66% did not answer	5.26% did not answer	All answered	All answered
It is a problem that can easily be solved by specialists		5.55%	0	6.66%	23.07%
It is the responsibility of the whole society, and it must take preventive and recovery measures in this regard		5.55%	0	6.66	23.07%
It does not affect us because we can continue buying food from Americans		0	0	13.33%	15.38%
It is not important because Mexico has a lot of territory and we can plant in other soils		77.77	94.74%	6.66%	7.69%
Problem 7	The profits from the food produced by the farmers	27.77% did not answer	5.26% did not answer	All answered	All answered
Should be for them so that they do not abandon their lands		5.55%	21.05%	33.33%	15.38%
It is correct that they should be mostly for the transporters because they bring them to the cities		0	0	33.33%	53.84%
Should be distributed according to the work and effort made by each one of them		66.66%	73.68%	26.66%	30.76%
Should be for the business owners because they are the ones who buy them to resell them		0	0	6.66%	0

TABLE 4 | Pre and post-concepts of children from the “Professor Alfonso Sánchez García” Institute and the “Leyes de Reforma” School.

Values and attitudes		Institute Sánchez García	Inst. Sánchez García	Leyes de Reforma school	Leyes de Reforma school
		Final	Initial	Final	Initial
		6° (18)	5° (19)	6° (15)	5° (13)
Problem 8	The peasants who abandon their lands and go to the U.S. as braceros	11.11% did not answer	5.26% did not answer	All answered	15.38% no contestó
They leave because the government does not support them		0	0	13.33%	30.76%
They leave because there is no work in Mexico, and we do not pay them fairly for their work		88.88%	89.47%	40.00%	30.76%
They leave because we prefer to buy foreign products instead of paying them fairly for their work					
They leave because they like to earn a lot of money		0	5.26%	13.33%	15.38%
Problem 9	Lupita’s aunt bought some plastic shoes made in China, which were cheaper than the leather shoes made in Mexico	33.33% did not answer	All answered	All answered	15.38% did not answer
She made a good purchase because they were cheaper		0	0	0	46.15
She did not make a good purchase because they are made of plastic and break more quickly		5.55%	10.52%	33.33%	15.38%
Even if the shoes made in Mexico were more expensive, she should have bought them, because by doing so she is helping other Mexicans keep their jobs		61.11%	78.94%	46.65%	15.38%
The only important thing is that she spent less		0	10.52%	20.00%	7.69%

9. There has been progress in understanding the economic problem of the market, but not enough; at least they are already reflecting on it.

It is significantly important to note that in the face of reflections that involve expressing their values, there were several questions in which the children simply abstained from expressing their opinion. The abstentions ranged from 5.26% to 33.33%, which affects the interpretation.

However, progress is perceived in 1) their reasoning in terms of conceptualizing the environment no longer as a stage, but as the environment in which they and other living beings develop. 2) they show a greater degree of responsibility when in their answers they indicate that it is they - and not only the government - who must demand that companies respect the environment, and they assume that part of the care that must be taken of it is their responsibility.

CONCLUDING STATEMENTS

Education for sustainability does not require the accumulation of a set of memorized concepts and knowledge. On the contrary, it is proposed that the challenge is to appropriate universal knowledge from broad epistemological perspectives, build collective values and principles, consolidate competencies to select them, reorganize them, transform them and build new links with practice, adapting them to the contexts of action at each moment and that the effort of daily work generates added value in terms of training and appropriation for students and teachers.

The change of beliefs, principles and values is more difficult to achieve than any change in statements or legislation, and only education for sustainability throughout the planet and from an early age can achieve the changes required to preserve natural resources and achieve the SDGs (Reyes-Sánchez, 2024).

Forming values to contribute to the integral development of human beings is an essential educational task for building sustainability, which is why it is necessary for both the school to work on its active formation and for the family to also collaborate to provide the knowledge and values that achieve a change in attitudes and beliefs that are reflected in ways of acting that allow preserving life on Earth.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

ETHICS STATEMENT

Like all educational research, this was conducted with students with the knowledge and participation of both children and schools and with the approval of both schools involved, which were aware of the fact that the children and their teachers were worked with for an entire school year. No specific ethical approval or consent procedures were required for this study. Acknowledgements to the children, teachers, and schools were also included in DOI: 10.3232/SJSS.2012.V2.N1.07.

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LR-S is first authorship. She conducted conceptualization; research; formal analysis; data curation; original draft writing and editing.

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CONFLICT OF INTEREST

The author declares that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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REFERENCES

Ausubel, D. P. (1973). *Psicología Educativa: Un Punto de Vista Cognoscitivo*. México: Trillas.

Belgrade, C. (1975). La Carta de Belgrado: Un Marco General Para la Educación Ambiental. Available at: https://unesdoc.unesco.org/ark:/48223/pf0000017772_spa.

Bernal, J. D. (1979). *La Ciencia en la Historia*. México: UNAM. Ed. Nueva Imagen.

Echeverría, J. (1995). El Pluralismo Axiológico de la Ciencia. *Isegoría* 12, 44–79. doi:10.3989/isegoria.1995.i12.240

Freinet, C. (1949). *L'éducation du Travail*. París, France: Editions Ophrys.

García, J. E. (2000). "Educación Ambiental y Ambientalización del Currículum," in *Didáctica de las Ciencias Experimentales*. Editor P. F. Perales (España: Alcoy Marfil).

Gómez, M., Margarita, R., Reyes, S., and Laura, B. (2004). Educación Ambiental, Imprescindible en la Formación De Nuevas Generaciones. *TERRA Latinoam.* 22 (4), 515–522.

Gutiérrez, J. (1995). *La Educación Ambiental: Fundamentos Teóricos, Propuesta de Transversalidad Y Orientaciones Extracurriculares*. Madrid: La Muralla.

Legrand, L. (1993). *Perspectivas. XXIII*, 1–2.

Makarenko, A. (1959). *Poema Pedagógico*. Progreso, México.

Meadows, D. (1977). *Limits to Growth: A Report for the Club of Rome's Project on the Predicament of Mankind*. E. U.A. New American Library.

Morales, M., Martínez, J.R.-S., Miranda, R. R., Martín Hernández, O., Arroyo Razo, G. A., Obaya Valdivia, A., et al. (2011). Qué Tan VERDE Es Un Experimento? *Educ. Quím.* 22 (3), 240–248. doi:10.1016/s0187-893x(18)30140-x

Novo, M. (1995). *La Educación Ambiental: Bases Éticas, Conceptuales Y Metodológicas*. España: Universitas S.A.

OEI (1995). V Conferencia Iberoamericana de Educación. Available at: http://www.oei.es/vcie.htm#urgencia.

Pardo, A. (1995). *La Educación Ambiental Como Proyecto*. España: Cuadernos de Educación. Número 18. Instituto de Ciencias de la Educación. Universidad de Barcelona.

Reyes-Sánchez, L. B. (2009). Propuesta Interdisciplinaria de Enseñanza y Aprendizaje de Las Ciencias de Orden Ambiental Para la Educación Básica, Utilizando el Suelo Como Recurso. Tesis Doctoral, ITCR-UNAM.

Reyes-Sánchez, L. B. (2012). Teaching Soil Science: Strategies and Guarantees for the Future. *Span. J. Soil Sci.* 2 (1), 87–99. doi:10.3232/SJSS.2012.V2.N1.07

Reyes-Sánchez, L. B. (2024). An Educational Gaze From the International Union of Soil Sciences. *Span. J. Soil Sci.* 13, 12208. doi:10.3389/sjss.2023.12208

Robert, M. (1985). *Unamuno y la educación*. SEP Cultura Ed. El Caballito.

UNESCO. (1971). Environmental Education. Available at: https://portals.iucn.org/library/sites/library/files/documents/Rep-1971-004-3.pdf.

UNESCO. (1987). *International Congress on Environmental Education and Training*. Moscú/París.

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REVIEW
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A Tribute to Jaume Porta Casanellas and His Influence on Soil Science

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This article provides personal and professional assessments from disciples, colleagues and friends of Jaume Porta Casanellas (Barcelona, 1944; Lleida, 2023), a prominent soil scientist. He began his agricultural engineering studies at the Polytechnic University of Madrid (UPM) where he met Marta López-Acevedo, his wife and outstanding collaborator. At UPM, he started his early work in soil science under the guidance of Professor Carlos Roquero who became his mentor and friend. Jaume Porta was a dedicated, passionate soil scientist who engaged extensively in teaching and research in Soil Science, while also excelling as a manager. He emerged as a leader due to his initiatives in promoting Soil Science in Catalonia and Spain, and for his forward-thinking vision, evident in his decisions as Rector of the University of Lleida, which have significantly contributed to the city's development. From the beginning, he advocated for detailed (1:25,000) soil mapping of Catalonia to enhance territorial planning and agricultural progress. His primary research focus was on salt-affected soils and soils with gypsum, alongside soil erosion and conservation. Porta devoted a lot of effort to improve soil field descriptions with his *Agenda de campo*. He played a key role in standardizing soil analytical methods, establishing large series laboratories in Spain, notably the LAF in Sidamon (Lleida), and aligning Spanish soil labs with the international GLOSOLAN network. As president of the SECS, he energized activities and encouraged member participation. His educational publications, mainly his comprehensive textbook *Edafología*, are considered fundamental in Soil Science across Spanish-speaking countries, as is the Multilingual Dictionary of Soil Science, representing the pinnacle of his efforts to rigorously disseminate soil science concepts and terms in Spanish, Catalan, Galician, and Portuguese. He contributed significantly to international Soil Science courses in Mexico and played a key role in establishing the JADE postgraduate training program. He facilitated the creation and international visibility of the Spanish Journal of Soil Science. Additionally, he advocated for the establishment of the Soil Sciences Documentation Centre

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(Ce.SECS) to preserve historical publications and the legacy of soil scientists. Jaume Porta's enduring impact, both professionally and personally, will be felt for years to come.

Keywords: soil education, history of soil science, multilingual dictionary of soil science (DiccMCS), SECS soil science documentation centre (Ce.SECS), soil information systems

INTRODUCTION

During the history of Soil Science, certain individuals emerge as milestones, shaping the landscape of knowledge and practice with their contributions. Among these figures stands Jaume Porta Casanellas, a distinguished leader whose influence has left an indelible mark on both research and academia. As we embark on this review paper, it is imperative to set the stage, providing context for the reader to appreciate the magnitude of Porta's impact.

This paper serves as a tribute to Jaume Porta. Unlike traditional research articles, this review paper is written by Porta's disciples, colleagues and friends, individuals whose lives and work have been profoundly touched by his mentorship and guidance. Here, we honour his legacy, celebrating his remarkable journey and the manifold ways in which he has advanced our understanding of soils.

As we delve into the various facets of Porta's contributions, it becomes evident that his influence transcends the boundaries of academia, from pioneering research to mentoring the next-generation of soil scientists and guiding policies and initiatives. Each section of this review paper offers insight into different aspects of his work, shedding light on the depth and breadth of his achievements.

THE EARLY YEARS

Jaume Porta Casanellas was born in Barcelona in 1944 and completed his secondary school in the *Lycée Français* in the same city. Despite being raised in an urban environment, he used to spend his summer holidays in a village in La Cerdanya, a valley in the Catalan Pyrenees (NE Spain). This exposure to the rural environment likely motivated him to pursue agricultural studies. After completing his Agronomy Engineer degree, he decided to specialize in Soil Science under the guidance of Professor Carlos Roquero de Laburu, Chair of Soil Science at Polytechnic University of Madrid. Around the strong personality of Carlos Roquero, a self-made man in Soil Science according to Jaume Porta, several agronomy engineers engaged in Soil Science. Some of them became Chairs of Soil Science in the Agronomy Schools across Spain in the 1980s and 1990s. Jaume Porta was one of them. With a Juan March fellowship, he undertook an advanced research stay (DEA) in Nancy (France), under the guidance of Professor Duchaufour. He later completed his PhD on salinity, vegetation and soils with gypsum in Alcázar de San Juan (La Mancha). Salt-affected soils and gypsum would remain central themes throughout his scientific career. During this period, he was in contact with the CSIC in Madrid, where Professor Covadonga Rodríguez Pascual was one of his mentors and supporters.

He was always mindful of the difficulties in studying soils, both in terms of approaches and methods, a perspective that likely dates back to these early years. Like his mentor Carlos Roquero, he believed that the study of soils should begin and end in the field. At a time when soil genesis and mineralogical studies were more appreciated than they are now, he often adopted a practical, applied approach to the study of soils. Initially, his studies focused on agronomy and soil conservation, eventually evolving into a more holistic approach. This "engineering" view on Soil Science was a consistent feature in his scientific and teaching activities.

Regarding methods, three aspects merit mention: field description, laboratory work, and soil classification. One of his early publications (1979), co-authored with Roquero, was the first version of field guide *Agenda de Campo,* which included a systematic description of the soil profile and many other relevant information for field soil characterization.

Professor Roquero was a key promoter of the use of Soil Taxonomy (Soil Survey Staff, 1975) in Spain, instead of other classification systems more common at a time (e.g., Kubiëna and the French CPCS system). Jaume Porta, despite or perhaps because of his knowledge of French, became a strong proponent of Soil Taxonomy. Throughout his career, he sought ways to teach it, clearly explaining the reasons for its use (Porta-Casanellas, 1985). In this task, he was always supported by his wife Marta López-Acevedo.

His tenure in the network of agronomy labs of the Spanish Ministry of Agriculture, though short, was very intense. It allowed him to understand the scientific and material weaknesses of the system and work to overcome them, by implementing adequate lab methods and developing large capacity labs useful for agriculture and Soil Science. This period also helped him to establish long-lasting scientific contacts, such as in Galicia. His interest in soil micromorphology dates from this period, recognizing from his PhD work that chemical analysis was not the best way to study soils with gypsum.

He always aimed to take an interdisciplinary approach to the study of soils, especially with Geology and Botany. For instance, his insistence on recruiting geologists and botanists for soil inventories and mapping studies, and his friendship with Professor Santiago Castroviejo, former Director of the *Real Jardín Botánico* in Madrid, date from this time.

RESEARCH AND UNIVERSITY CAREER IN CATALONIA: FROM THE GROUND TO THE RECTORATE OF LLEIDA UNIVERSITY AND THE STRUGGLE TO DEVELOP AND CONSOLIDATE SOIL SCIENCE

After his arrival to Lleida in 1977 he began working in the Higher Technical School of Agricultural Engineering (ETSEA), which at that time belonged to the Polytechnic University of Barcelona (UPB). His goal was always to make Soil Science influential in society. During that period, it seemed that everything was possible. His generation was in a privileged position, and he actively pursued this potential both in academia and in society. From the outset, he aimed to identify lines of work and/or research relevant to his territorial and social environment, engaging with them while also positioning his followers in a global context.

He devoted significant effort to attracting and engaging promising students in the field of Soil Science and later did the same with talented individuals for his projects. He succeeded in teaching the importance of soil to his agronomy engineering students, emphasizing its essential role in all their future engineering activities. In the early years, he put considerable effort into training graduate students in Soil Science through specific *ad hoc* courses featuring numerous outstanding lecturers.

Recognizing that Soil Science was not a main focus at the ETSEA, he worked hard to make professors in related areas sensitive to the importance of Soil Science. We now recognize all these actions as a long-lasting, strategic project that was one of the main strengths of his career.

A hardworking and reserved man, he pursued his aims, ideas, and objectives with great tenacity for many years, convinced of their correctness. Although he was not always easy to work with, his actions and ideas resulted in many devoted followers, as well as disagreements that sometimes lasted too long and were not fully understood.

The Academic Career

In the 1977/78 academic year, two young professors, Jaume Porta and his wife Marta López-Acevedo, joined the ETSEA. From the very beginning, both were highly active trying to consolidate an academic project in Soil Science. They created the Department of Soils and Climate, where they worked on research projects involving soil salinity and drainage, soil erosion and conservation, and soil fertility in various areas of the region. This included a focus on the nutrition of hazelnut (*Corylus avellana* L.) and its pedoclimatic environment as well as practical applications of Soil Science such as soil assessment, soil inventories and mapping. They were diligent about publishing their results in *ad hoc* publications, which were carefully -and painstakingly- prepared with the limited resources at the time.

From the start, both professors dedicated their efforts to training agronomists in Soil Science (soil fertility, soil classification, soil mapping, land evaluation) and organizing courses in land use planning. Recognizing that Soil Science was often seen as secondary to other sciences, they worked to strengthen the connections and actions of soil practitioners in Catalonia and abroad.

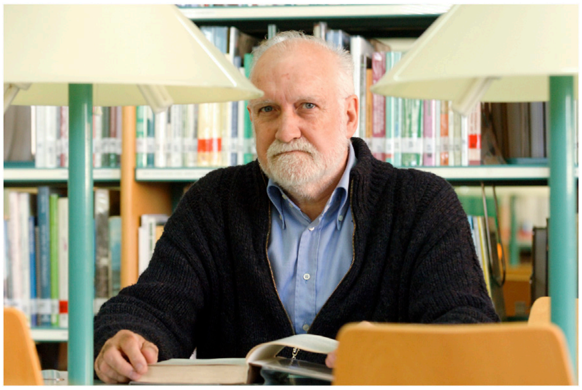

FIGURE 1 | Libraries were one of Jaume Porta greater passions. Image at the ETSEA library of the University of Lleida (Photo by Toni Prim).

In 1978, Jaume Porta joined the ETSEA board of directors as vice-director of research, and in 1984 he was elected director of the ETSEA, a position he held until 1987. During this period, he focused on consolidating existing degree programs, planning new ones, and developing infrastructure from the initial stages of the "*Agrònoms*" campus (Porta et al., 2013). In 1986, he became Full Professor of Soil Science with a dissertation on the genesis of petrocalcic horizons.

In 1992, a "*Comisión Gestora*," led by Professor Víctor Siurana, was appointed to manage the creation of the University of Lleida (UdL). Jaume Porta was one of the three vice-presidents of this commission until his election as the first Rector of the UdL in May 1993. He remained in this position for 10 years, from May 1993 to May 2003.

It is interesting to note that the University of Lleida, founded in 1300, was the oldest university in Catalonia. It was closed in 1717 after the War of Succession, and it was not until 1991 that the UdL was reestablished. Jaume Porta took advantage of this circumstance to organise the celebration of the 700th anniversary of the University of Lleida (1300–2000), as the oldest in the Crown of Aragon, repositioning it in the national and European university landscape (Porta, 1996). This allowed presenting it as a first-rate asset for the city of Lleida and obtaining significant resources for its development. Jaume Porta defined himself as a "university professor who likes to look far ahead" (Andreu-Gasa and Villar-Mir, 2018). Those of us who had the good fortune to work closely with him, especially during his tenure as Rector of the University, would emphasize his leadership, his innovative and creative character, and his great working capacity, always with a long-term vision and with the decisive mission of educating people in a holistic manner.

Among his passions were architecture and libraries. The libraries of the University of Lleida were a priority subject of his governance (**Figure 1**). The main library of the UdL, now called the "*Biblioteca Jaume Porta*," was the result of an international competition organised by the UdL to commemorate the 700th anniversary of its foundation. The winners were the Finnish architects Kristian Gullichsen and Timo Vormala, the authors of a unique and emblematic building at the entrance to the *Cappont* campus (Benedito and Benedito, 2001). On the same campus, the Faculty of Education Sciences is located, designed by Alvaro Siza, an outstanding and renowned Portuguese architect. The involvement of important architects was another result of Rector Porta's determination to leave an architectural legacy to the University and to the city of Lleida, his adopted city as he always remembered. His university vision and his love for the city of Lleida, combined with his tenacious character, made it possible to achieve a legacy of excellent architecture. A virtual tour can be enjoyed at the following link.[1]

Jaume Porta loved books. In addition to his teaching books on Soil Science, he coordinated collective works such as *La universidad en el cambio de siglo* (Porta and Lladonosa, 1998), the *Biblioteques Imaginàries de la Universitat de Lleida* (Porta, 1997), *Descobrir Lleida passejant per l'arquitectura del segle XX* (Porta, 2005) and *Álvaro Siza a la Universitat de Lleida* (Cornadó and Porta, 2007). The government team led by Jaume Porta supported from the beginning the cultural and artistic promotion that culminated with the ten artists project around the 700th anniversary of the UdL (Porta, 2001). Promoting the internationalisation of the university and student mobility were also priority actions of his mandate (Porta, 2003). He created, for instance, the JADE program to facilitate exchanges with Mexican universities (see *Activity in Mexican Universities. International Soil Science Course, UNAM* section).

In 2014 he was appointed Professor Emeritus of the University and until his retirement in 2019 he was an outstanding member of the Department of Environment and Soil Sciences, continuing with his teaching, research and knowledge transfer activities.

Research

Since the early 70s of the XX Century, different research topics on soil genesis and soil degradation and conservation aroused the interest of Jaume Porta. Compiling all his works is a difficult task since some of them are unpublished reports, engineer final projects or PhD theses he supervised. Later, during the time as rector of the UdL, his main dedication was management, although he never abandoned his commitment with doctoral students, lecturers, and colleagues eager for his knowledge. Below there is a summary of the main research topics in which Jaume Porta worked, although, as it has been said, it is by no means a complete list.

Soils With Gypsum

One of the main research topics of Jaume Porta was the study of soils with gypsum, to which Soil Science had paid little attention until that time, leading to misconceptions on their composition and behaviour. One of his first works was his PhD thesis about ionic redistributions in saline soils, the influence on halophytic vegetation and the possibilities of reclamation of halomorphic soils, and soils with a gypsic horizon (Porta, 1975). This work involved a deep revision of the main methodologies and techniques used to characterise gypsum in soils in the field and in the laboratory on soils of semiarid and arid regions (Porta, 1998).

Together with Juan Herrero and Nicolas Fedoroff, Jaume Porta contributed to define and coining specific terms with precise meanings for gypsum forms in soils. Examples are *lenticular gypsum*, *microcrystalline gypsum*, *gypsic fabric*, *lenticular gypsic fabric*, *microgypsic fabric*, *isles fabric* and *queras* (Porta and Herrero, 1990; Herrero et al., 1992; Herrero and Porta, 2000). From then on, these terms were joined to those already existing for the description of secondary accumulations of gypsum (vermiform accumulations, noduli, rhizocretions and cemented horizons), helping to better describe the wide range of forms that gypsum can adopt in horizons of arid and semi-arid soils. Among the study methodologies, particular attention received the micromorphological approach (Porta and Herrero, 1990). They described lenticular crystals, as the most common form of pedogenic gypsum, which in more advanced stages could become a continuous or massive accumulation. He experimentally demonstrated that the lenticular habit develops in the presence of organic matter. Moreover, Porta and Herrero (1990) found that the weathering of outcropping gypsum rock may lead to a microcrystalline gypsum mass that is easily transported by mudflows. Herrero et al. (1992), in his PhD thesis supervised by Jaume Porta, contributed to the study of hypergypsic soils and the development of terminology describing these soils. In this research, they concluded that the introduction of the hypergypsic diagnostic horizon to the taxonomic classification system would be helpful for the accurate classification of these soils. Later, the co-supervision of the PhD thesis of Rosa M Poch (Poch, 1992) enlarged the knowledge of soils with gypsum in Quaternary materials. In short, in this research field Jaume Porta and his collaborators made significant advances to better reflect the genesis of soils with gypsum as well as their behaviour under both natural and artificial conditions, helping to understand the role of gypsum in local and global earth-surface processes (Herrero and Porta, 2000; Casby-Horton et al., 2015).

Soil Erosion, Degradation and Conservation

Another research line of interest for Jaume Porta was soil erosion and conservation in different environments, such as the stone wall terraces of the Catalonian Meridional Area, vineyard soils of the Anoia and Penedès region and surface-mined soils of the pre-Pyrenees. Porta and Julià (1983) published a study covering 90,000 ha of the Catalonian Meridional area highlighting the importance of the stone wall terraces for soil and water conservation and as a soil forming process.

In the vineyard soils of the Anoia-Penedès region, Porta and his collaborators initially focused on soil conservation in the early 1980s. Later, their interest shifted to quantify and estimating soil and nutrient losses due to hydric erosion, driven by the economic impact of this crop in the region. Rainfall intensities exceeding 100 mm h^{-1} in 5-min periods are common in the area, giving rise to high runoff rates and significant erosion processes in fields (rill

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[1] https://biblioguies.udl.cat/passeigarquitectonic

FIGURE 2 | Jaume Porta measuring a trapezoidal hillside ditch (locally named "*rasa*") in the Penedès vineyard area (Photo courtesy of M.C. Ramos Martín, dated in 1990).

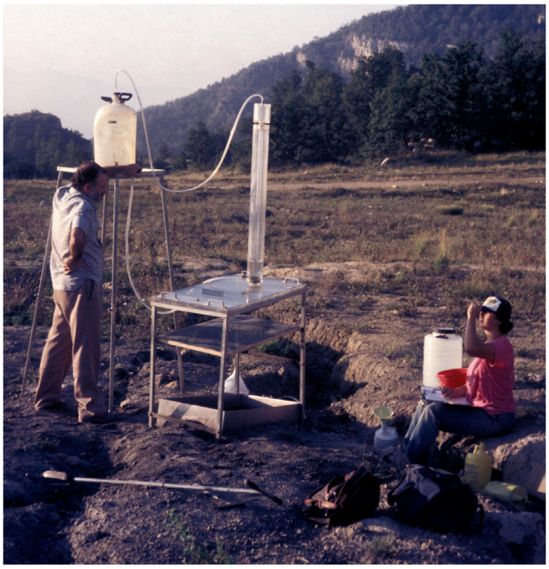

FIGURE 3 | Jaume Porta and Rosa M. Poch measuring soil losses with a rainfall simulator in Sant Corneli, a restored mine located in the Berguedà county (North of Catalonia) (Photo by José A. Martínez-Casasnovas, dated 1985).

erosion) and at the heads and sidewalls of gullies (Ramos and Porta, 1994). Porta and Ramos (1993) documented substantial soil losses, ranging from 10 to 100 Mg ha^{-1}, resulting from single autumn rainfalls. Nutrient losses were also important, with N losses between 9 and 90 kg ha^{-1}. They later evaluated the effectiveness of conservation measures like hillside ditch terraces, locally named "*rases*", which were common in vineyards before massive land transformations began in the 2000s. They found that empirical criteria used by farmers were inefficient, requiring a reduction in inter-terrace distance from 40 m to about 28 m (Ramos and Porta, 1997) (**Figure 2**). Regarding gully erosion in this region, Martínez-Casasnovas and Porta (1999), found gully retreat rates of 0.2 m y^{-1} and soil losses of 917.9 Mg ha^{-1}, which are comparable to catastrophic landslides.

In restored surfaced-mined areas, Porta's interest in studying erosion processes was driven by the opportunity to implement and test erosion control practices. These included bench terraces to infiltrate water on the lowest part of the restored surface and sowing grasses and legumes over the spoil banks. Research beginning in 1983 (Porta et al., 1983), showed that when conservation measures were used without a good understanding of surface hydrological processes, erosion occurred from the start of rehabilitation, rendering conservation measures useless and sometimes exacerbating the problem (Porta et al., 1988) (**Figure 3**).

In addition to the research carried out on salt-affected soils and erosion, Jaume Porta, along with Rosa M. Poch studied land degradation caused by human activities using the DPSIR framework (Porta and Poch, 2011). This framework describes interactions between driving forces, pressures, states, impacts and responses to long-term land use changes associated with each specific land and soil degradation problems (Porta, 2009). Their work revealed that socioeconomic and sociocultural driving forces increased pressure on the analysed systems and that technical measures alone were insufficient to prevent or control land and soil degradation. Effective responses needed to address driving forces and apply scientific principles of soil behaviour in response to land use changes, otherwise, pressures would persist, and problems would reoccur.

Irrigation and Salt Affected Soils

Jaume Porta's research on salt-affected soils (salinization and alkalinization) began with his PhD thesis, where he studied these soils by means of soil analysis and of halophytic vegetation communities (Porta, 1975; Porta et al., 1980). This research expanded to include salt-affected soils in Huesca province (Aragón, Spain), where irrigation led to salinization and alkalinization processes (Porta et al., 1986a). Initially, they applied the USBR and FAO evaluation systems for land evaluation for irrigation in the Flumen-Monegros system. They concluded that salinization, alkalinization or drain siltation were mainly due to soil characteristics and, to some extent, the quality of irrigation water, which was not initially considered. Subsequent studies by Herrero et al. (1989) and Rodríguez et al. (1990) used micromorphological methods to validate indices for predicting soil suitability for drainage, and to characterize the drain siltation processes in the Flumen-Monegros area. All these research works provided a general overview of the vulnerability of soil degradation under irrigation (Porta and Herrero, 1996).

Land Evaluation

Noteworthy contributions in land evaluation date from the 1980s. The Cadastral Management and Tax Cooperation Centre of the Spanish Treasury promoted the development of a method for the assessment of the value of the land in relation to its agricultural

FIGURE 4 | Jaume Porta and Jaume Boixadera during the field excursion of the "XVI Reunión de la Sociedad Española de la Ciencia del Suelo" (Lleida 1989) explaining the characteristics of a typical soil profile of the semi-arid soils of the meridional area of Lleida (Photo by Rosa M. Poch).

use. Boixadera and Porta (1991) developed the "Index Value Method" based on the FAO (1976) framework for land evaluation. This method evaluates land productivity potential and suitability for different uses, allowing for more objective and uniform application across territories.

Soil Genesis and Classification

In soil genesis and classification, Porta and Julià (1983) described the main soil-landscape relationships, the genesis of petrocalcic horizons, the pedological and geomorphological processes in the slopes and ancient terraced slopes, and the origin and mobilization of gypsum and more soluble salts in the soils and in the landscape of the Catalonian Meridional area (**Figure 4**). They identified limitations in existing models for determining the water regime of soils in arid or semi-arid areas, such as the southern area of Catalonia. Jarauta (1989) in his PhD thesis supervised by Jaume Porta, improved Newhall's model for determining soil moisture regimes. This was a key issue for characterizing soils developed in semiarid areas of Catalonia, where the transition between the xeric and aridic regimes depends on soil properties (Jarauta et al., 1989). This method is still used today to define the soil moisture regimes in Catalonia (ICGC, 2019).

Soil Mapping and Soil Inventories

Els sòls de Catalunya: àrea meridional de Lleida (Porta and Julià, 1983) is one of Jaume Porta's first works of on soil inventories. At that time, knowledge of these soils was so limited and resources so scarce that presenting a soil map of any scale was impossible. Nevertheless, this work contained the main features of a soil inventory and later served as a model for soil surveys in this and other surrounding areas of western Catalonia. From the outset, key issues for the mapping tasks promoted by Porta included fundraising, the availability of trained staff and access to soil laboratories.

The soil map of Barcelona Province, promoted by Barcelona Provincial Council, represented a significant step forward, though few municipal maps were created and only two were fully published. At that time, Jaume Porta became convinced that soil maps should be useful, which in a small country like Catalonia, is only possible with detailed-scale (at least 1: 25,000) soil maps.

These and other soil mapping exercises highlighted several key requirements from the beginning: the need for a manual to describe the soils, the importance of storing information digitally despite limited computer facilities, and the necessity of a properly equipped laboratory for analysis. To address the first issue, Porta developed a comprehensive manual from the "*Agenda de Campo*" (Roquero and Porta, 1979) with codified information for digitalization. This was a novel approach at the time when computers were just emerging. To ensure consensus, a commission comprising prominent Spanish pedologists and soil mappers was established, and the Spanish Ministry of Agriculture supported this effort. The resulting manual was published as SINEDARES (Comisión del Banco de Datos de Suelos y Aguas, 1983). In Catalonia, a regional Soil Data Bank was created using an adapted SINEDARES system (CatSIS). Despite the sound idea, resources were insufficient, and awareness of the importance of soil surveys was limited, leaving most of Spain still needing comprehensive soil mapping.

Another soil mapping project initiated by Jaume Porta began in 1984 under the *Generalitat* of Catalonia, which is now proved fruitful. By the time it started, some challenges related to soil description and analysis had been partly addressed. In 1994, the first sheet of the Soil Map 1:25,000 of Catalonia was published (Herrero et al., 1993) Later, it became necessary to find a suitable institution for conducting the soil mapping exercise to ensure quality and accuracy. This role was first taken on by the *Servei Geològic de Catalunya* and later by the *Institut Cartogràfic i Geològic de Catalunya* (ICGC) (**Figure 5**). In these organisations, Emilio Ascaso Sastrón and his team found the appropriate environment to create the Soil Map 1:250,000 of Catalonia, gather new information at 1:25,000 and make all of it accessible online and useful. During this period, Porta played a crucial role in transferring the Soil Map of Catalonia to the ICGC, overcoming many obstacles with his invaluable assistance, support, and guidance, including the essential training of soil surveyors.

Jaume Porta and the Impulse of Soil Analysis Laboratories

Soil analysis laboratories are a strategically valuable asset in the development of Soil Science. Their proper functioning allows the characterization of physical, chemical, and biological properties through the collection of analytical data generated by specific, validated, and standardized procedures.

In the late 1960s and early 1970s, Jaume Porta recognized the need for facilities with sufficient capacity and reliability to meet the demands of research, mapping, fertilisation recommendations and soil characterization work (Porta et al., 1994). He was closely involved in the creation of the Regional Agricultural Laboratories, a project driven by agronomic engineer Rafael García Faure under the Directorate General of Agriculture, led by Ramón Esteruelas, from the Ministry of Agriculture of

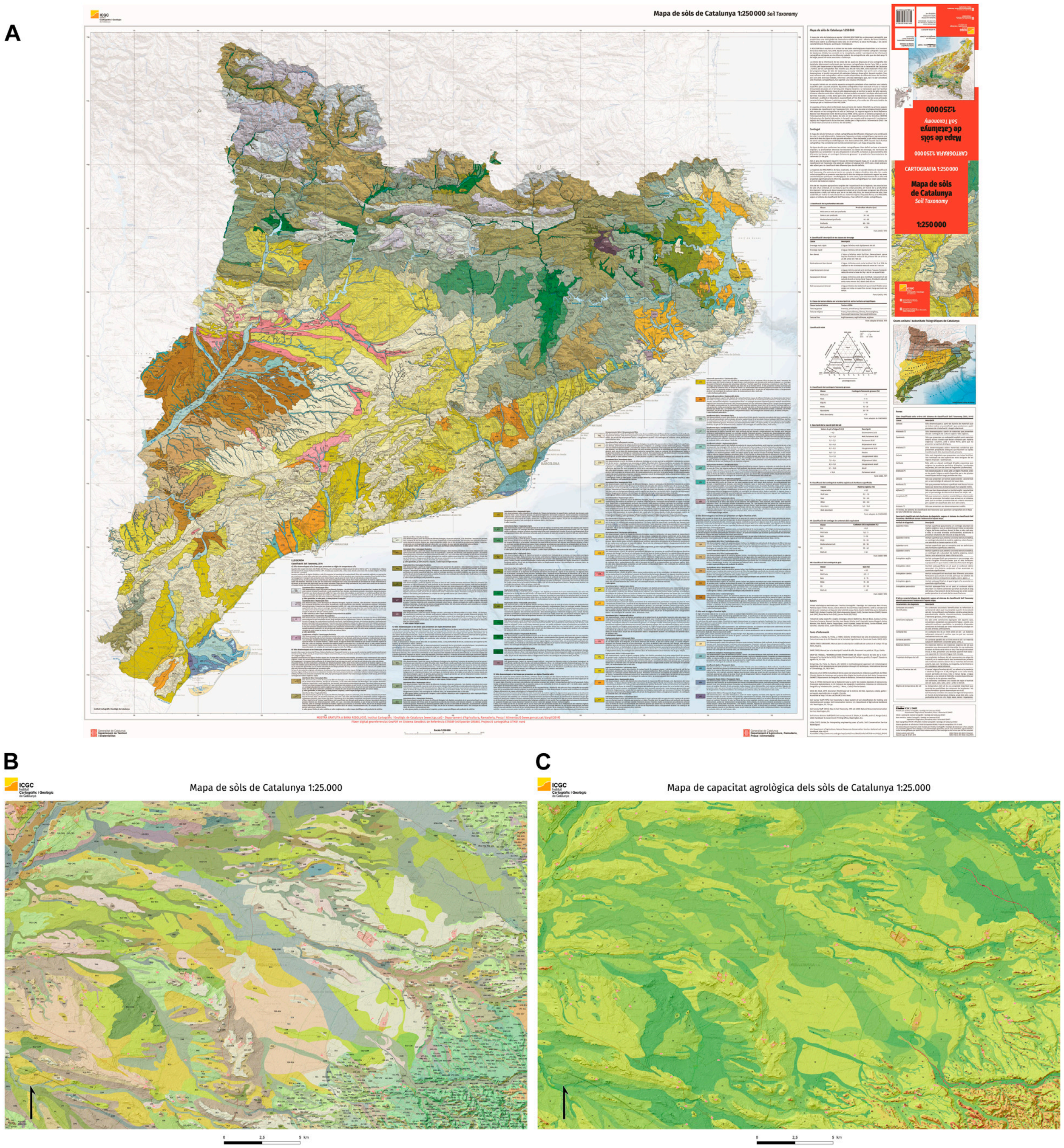

FIGURE 5 | Jaume Porta contributed very significantly to the mapping of the soils of Catalonia, both by convincing administrators and stakeholders of the need for a detailed soil map and training students. Miniature of the 1:250,000 soil map [**(A)**, upper], and a sample of the soil [**(B)**, left] and derived land capability [**(C)**, right] 1: 25,000 maps published by the ICGC (Extracted from open access images of Institut Cartogràfic i Geològic de Catalunya (ICGC) according to Creative Commons 4.0 international license CC BY 4.0).[2]

Spain. As an agronomic engineer, Porta began his professional career at the Regional Agricultural Laboratory of Guísamo (A Coruña), later moving to the Regional Agricultural Laboratory of Ebro (Zaragoza) and the Regional Agricultural Laboratory of Madrid, before joining ETSEA as a Soil Science professor. This experience provided him with first-hand knowledge of the laboratories' needs in terms of design, construction, staffing, and technological equipment (Porta, 1974).

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[2] https://www.icgc.cat/en/ICGC/Public-Information/Transparency/Re-use-information

In the 1980s, alongside the creation of soil laboratories, the publication of the book "*Técnicas y experimentos en Edafología*" (Porta et al., 1986b) comprehensively detailed classical analytical procedures used in soil laboratories. It embodied the didactic and accessible style that characterized Jaume Porta's later works, facilitating access to Soil Science for students, professors, scientists, researchers, and various professionals. The work of the "*Comisión de Métodos Oficiales de Análisis de España*" is also notable for its impact on analytical procedures, establishing methodologies for the main soil analytical determinations (MAPA, 1986).

In Lleida, Jaume Porta, with support from the Provincial Council, established a suitable soil laboratory to meet educational, research, and experimentation needs in soil and plant analysis. In 1980 this laboratory was equipped with a powerful atomic absorption spectrophotometry device, under the guidance of Marta López-Acevedo, serving as an excellent training ground for laboratory work. Numerous analytical vocations originated from these facilities.

Recognizing the need to advance Soil Science in support of the agricultural sector, Jaume Porta developed the idea of creating a high-performance soil laboratory capable of processing large volumes of soil samples with high reliability. Through intense efforts and perseverance, in 1987, together with agricultural engineer Josep María Villar, he presented a project for an automated soil laboratory to the Provincial Council of Lleida (Porta and Villar, 1987). The designed centre envisioned a future with a high degree of automation, innovative design, and equipment matching the sector's needs. With support from agricultural engineer Francisco Juárez, also a professor at the University of Lleida, a laboratory development program was designed, considering the need for active sample collection to ensure the laboratory's long-term economic sustainability. This development model was inspired by laboratories in France and the Netherlands, characterized by a network of private or public-private laboratories coexisting with powerful state laboratories (Baize, 2000).

Designing an economically sustainable laboratory was a key challenge that required a new approach, considering not only quality criteria but also analytical response speed, promotion of services, and integration into a sector with little inclination to pay for analytical services. This context spanned the late 1980s and early 1990s.

Finally, in 1992, the "*LAF, Laboratori d'Anàlisis i Fertilitat de Sòls*" was inaugurated in Sidamon (Lleida). This laboratory, operating as a joint-stock company (*Servei d'Anàlisis de Sòls-Diputació de Lleida S.A.*), was promoted by the Provincial Council of Lleida with the participation from the agricultural cooperative sector and the University of Lleida, turning previous projects into reality. The laboratory included advanced equipment, semi-automated analysis lines, and a strategy for service promotion and analytical result interpretation. ETSEA significantly supported the project through Jaume Porta's initiative, providing crucial institutional support during the start-up and implementation period. This laboratory successfully achieved its growth and sample volume projection plan. Years later, it was acquired by the certification company Applus+ (2005), and subsequently by the Eurofins analysis group (2014). The laboratory has analysed large volumes of soil samples and played a significant role in soil mapping, fertilisation recommendations, implementation of analytical control regulations in the agricultural sector, plant nutrition advice (Villar and Aran, 2008), and various projects, constituting an interesting analytical development model.

Despite his prominent role in the governing bodies of the University of Lleida (1993–2003), Jaume Porta continued to participate in areas related to soil laboratories, offering his experience and network of contacts, and participating in numerous initiatives, maintaining a close connection with the development of the Sidamon laboratory.

One of his objectives in recent years was the establishment of a National Reference Laboratory (LNR) in Spain to act as a centre for support, connection, coordination, testing new analysis methodologies, method harmonization, and as a reference for the public and private soil analysis laboratories ecosystem in Spain. This objective aligns with the GLOSOLAN project (Global Soil Laboratory Network) (FAO, 2020) under the framework of the Global Soil Partnership. In essence, Porta envisioned GLOSOLAN as an excellent initiative to connect Spanish laboratories and the LNR with this international network.

For his work and projects in the conception, development, and support of soil laboratories, Jaume Porta made a significant and decisive contribution to this branch of Soil Science. His influence was crucial in advancing soil analysis as a fundamental support in soil studies.

Jaume Porta, a Leading Figure of Soil Science in Catalonia

In 1977, he arrived in Catalonia as a professor at the newly established ETSEA, during a time of significant changes and opportunities. From the outset, he recognized the need to create spaces, resources, and activities to develop Soil Science in Catalonia, a field deeply connected to the region. He aimed to engage soil scientists by seizing every possible opportunity or creating new ones.

The dispersion of soil scientists across various institutions and geographical locations in Catalonia posed challenges in fostering connections among them, promoting knowledge of Catalan soils and exchanging experiences. In the early 1980s, most Catalan soil scientists associated with the agricultural sector belonged to the Catalan Institution of Agrarian Studies (ICEA, 2024), linked to the Institute of Catalan Studies (IEC). Jaume Porta, with the support from his colleagues Ricard Danés and Narcís Teixidor, initiated the creation of a Soil Group within the ICEA in the mid-1980s. As its activities expanded, this group became the Soil Section of ICEA in 1991 (Secció de Sòls de la ICEA, 2024).[3]

However, ICEA did not encompass all individuals interested in Catalan soils, particularly those in academia or research, who

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[3] https://icea.iec.cat/seccions/sols/

were mostly members of the Spanish Society of Soil Science (SECS). SECS focused on organizing congresses, courses, and field trips across Spain, but direct contact between members was somewhat limited. To address this, Jaume Porta, pioneered the establishment of regional groups in 2012, creating the first Territorial Delegation (TD) of SECS in Catalonia, which was followed by those of other regions in Spain. This proximity facilitated the organization of in-person activities.

Identifying the individuals interested in Soil Science in Catalonia, the next step was to strengthen the bonds through joint activities. Since 1985, documented conferences, technical sessions, visits to centres, and field trips to study or observe soil-related issues have taken place. Among these activities, the *"Transcatalonia"* stand out. It consists of a field day to observe the soils of a specific locality or region in Catalonia, including their use and management, supported with a field guide and a friend lunch. A significant step was appointing the same person to lead both the Soil Section of ICEA and coordinate SECS members in Catalonia, even before the creation of respective TD. This role was assisted by another member acting as secretary, ensuring maximum coordination. Jaume Porta served in this role from 1988 to 1991, before being elected president of SECS. Another noteworthy initiative was the creation in 1989 of a list of books and journals related to Soil Science available in Catalan universities and other institutions' libraries, long before internet portals appeared. This list, distributed among Catalan SECS and ICEA Soil Section members, included journal titles, issues, locations (e.g., Soil Science library at the Faculty of Pharmacy), and conditions for consultation. In some cases, photocopies of desired articles could be requested by mail or phone from colleagues at those institutions. This initiative helped alleviate the economic constraints faced by universities and public research centres for journal subscriptions, avoiding duplications and coordinating new subscriptions across different entities where Catalan soil scientists worked.

Jaume Porta stood out for his leadership and initiative, resulting in a period of heightened activity in the Soil Section of ICEA and TD of SECS. He succeeded in bringing together most soil scientists in Catalonia through these initiatives, particularly the younger ones in their scientific growth phase.

An example of his leadership was his role as coordinator of a collective book on soils, involving eight soil scientists from five different institutions in Catalonia and the University of Valencia, published in 1985. This extensive chapter on soil was part of Volume 3 of the encyclopaedia *"Història Natural dels Països Catalans,"* a comprehensive, well-edited and illustrated work, serving as a reference for many years. Due to its quality, this chapter was also published as an independent book by the College of Agricultural Engineers of Catalonia under the title *"Introducció al Coneixement del Sòl: sòls dels Països Catalans"* (Porta et al., 1987). This work, along with many of his other publications, demonstrated his commitment to disseminating the Catalan language and culture with precision.

From 1997, he became a member of the Science and Technology Section of the Institute of Catalan Studies, contributing valuable efforts to compile and disseminate terminology specific to Soil Science. He also created the website "*Protecció de Sòls*,"[4] containing historical soil maps, links to current cartography, and other relevant soil information.

Even when other positions of greater responsibility demanded his attention, Jaume Porta remained an active member of ICEA and SECS in Catalonia, participating in the organization of national and international congresses and scientific meetings, and engaging in most activities held in Catalonia.

JAUME PORTA: A VISIONARY EDUCATOR AND PIONEERING IN SOIL SCIENCE

Jaume Porta, a dedicated scholar and educator, left an indelible mark on the field of Soil Science, particularly through his relentless efforts to develop teaching materials that catered to students at all levels. His passion for education was evident in his focus on creating practical and useful manuals and books, rather than chasing citations or scientific indices. A list of his main educational publications is found in **Table 1**.

One of his earliest contributions was the co-authorship of the "*Agenda de Campo para el Estudio del Suelo*" alongside Carlos Roquero. This project, initiated with local editions in 1979 by the Polytechnic University of Madrid, was much more ambitious than the FAO Guidelines for soil profile descriptions and aimed to be the Spanish equivalent of the Soil Survey Manuals of the USDA. By 1995, the "*Agenda*" had reached its 7th edition and 191 pages. Later a very much expanded version (541 p) was published by Mundi-Prensa in 2005, with Marta López-Acevedo joining as a co-author (**Figure 6**).

Recognizing the absence of a comprehensive textbook on Soil Science in Spanish, Porta, along with Roquero and López-Acevedo, published "*Edafología para la agricultura y medio ambiente*" in 1994. This textbook, which went through three editions by 2003, filled a crucial gap in the educational resources available to Spanish-speaking students.

Porta's visionary approach extended to addressing the evolving landscape of education. With the launch of the European Higher Education Area (EHEA) in 2010, he identified the need for materials that allowed students to engage in independent learning. Collaborating with Marta López-Acevedo and Rosa M Poch, he proposed an interactive book titled "*Introducción a la Edafología. Uso y protección del suelo*" (**Figure 6**). This groundbreaking work, published in 2008 and 2010, later evolved into "*Edafología. Uso y protección de suelos*" in subsequent editions (2014 and 2019). It became a cornerstone for several generations of soil scientists in Spain and Latin America.

Porta's commitment to linguistic precision was evident in his endeavours to standardize Soil Science terminology. In 1989, he promoted and co-authored the "*Lèxic de la Ciència del Sòl*" in Catalan, providing equivalents in Spanish, English, and French. He was particularly meticulous about using the term "*edafología*" in Spanish to accurately represent Soil Science, as opposed to the

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[4] https://www.iec.cat/mapasols/Ang/Inici.asp

TABLE 1 | Main educational publications of Jaume Porta Casanellas.

Porta, J., López-Acevedo, M. and Poch, R.M. (2019). Edafología. Uso y protección de suelos. Ed. Paraninfo. 3rd ed. ISBN: 978-84-8476-661-2; 4th Ed. ISBN: 978-84-8476-750-3
Porta, J., López-Acevedo, M. and Poch, R.M. (2010). Introducción a la Edafología. Uso y protección del suelo. Mundi-Prensa, 2008, ISBN: 978-84-8476-342-0; 2nd Ed. 2010, ISBN: 978-84-8476-405-2
Porta, J., López-Acevedo, M. and Poch, R.M. (2009). IIntroducció a l'Edafologia. Ús i Protecció de Sòls. Mundi-Prensa, 507 pp. ISBN: 978-84-8476-385-7
Porta, J., López-Acevedo, M. and Roquero de Laburu, C. (2003). Edafología: Para la Agricultura y el Medio Ambiente. Mundi Prensa Libros, 1994 ISBN: 84-7114-468-9; 1999 (2nd Ed.). ISBN 84-7114-784-X; 2003 (3rd Ed.) ISBN: 84-8476-148-7
Porta, J. and López-Acevedo, M. (2005). Agenda de Campo de Suelos. Información de Suelos Para la Agricultura y el Medio Ambiente. Mundi Prensa Libros, 541 p. ISBN 84-8476-231-9
Roquero de Laburu, C. and Porta, J. (1995) Agenda de campo para el estudio del suelo. Universidad Politécnica de Madrid, 1979 (2nd Ed.). ISBN 84-7401-058-6; 1995 (7th Ed.). ISBN 84-7401-058-6
Porta, J., López-Acevedo, M. and Rodríguez-Ochoa, R. (1986). Técnicas y Experimentos en Edafología, Col·legi Oficial d'Enginyers Agrònoms de Catalunya. ISBN 84-600-4341-X
Porta, J., Rodríguez-Ochoa, R. and López-Acevedo, M. (1993). Laboratori d'Edafologia. Universitat Politècnica de Catalunya, 1993. ISBN 84-7653-252-0
Porta, J., Ferret, M., Teixidor, N. and Poch, R.M. (1989) Lèxic de la Ciència del Sòl, Català/Castellà/Francès/Anglès. Universitat Politècnica de Catalunya, 115 pp. ISBN 84-7653-038-2
Porta, J. and Villanueva, D. (2012). Formación de Neologismos en Ciencia del Suelo. Spanish Journal of Soil Science, 2012, vol. 2 (2), p. 90–103

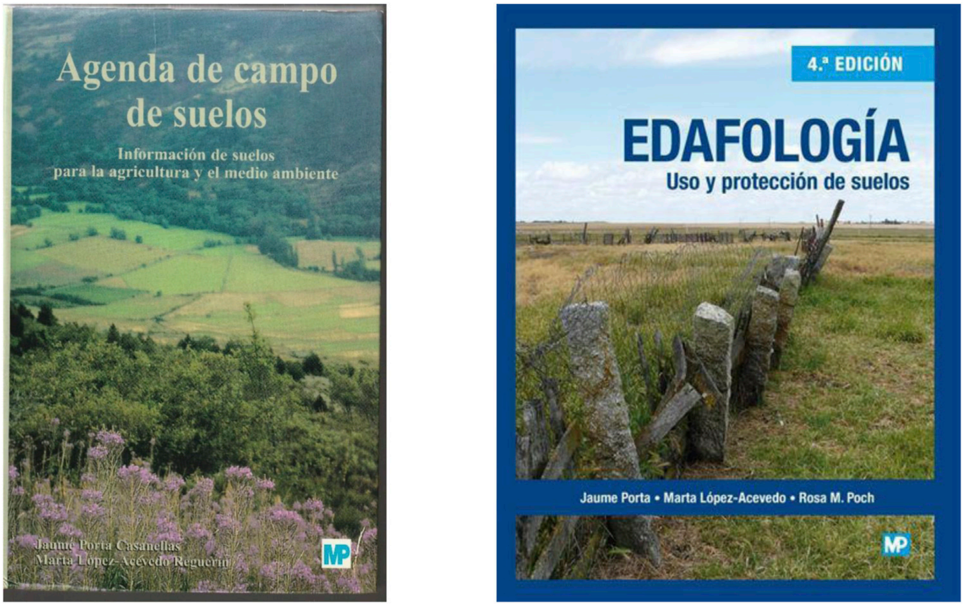

FIGURE 6 | Cover of the two remarkable books of Jaume Porta, coauthored with Marta López-Acevedo and Rosa M. Poch, edited by Mundi-Prensa: A, the *Agenda de campo de suelos*; B, the 4th edition of *Edafología, Uso y Protección de suelos*.

potential confusion with the term "edaphology." This dedication to linguistic clarity led him to publish a paper with Darío Villanueva from the Real Academia de la Lengua Española in 2012, where they clarified the different meanings and equivalences of terms like Soil Science, pedology, and edaphology.

Among his many influential works, "*Técnicas y Experimentos en Edafología*" (1986b) stands out as a widely cited and utilized resource detailing basic soil analyses in standard laboratories. Porta's commitment to linguistic accuracy extended to this work with a partial translation into Catalan in 1993.

Jaume Porta's legacy in the realm of Soil Science education is marked by his unwavering dedication to providing accessible and practical resources for students at every stage of their academic journey. His vision, commitment to linguistic precision, and passion for teaching continue to shape the education and understanding of Soil Science in Spain and beyond.

JAUME PORTA'S CONTRIBUTION TO THE MULTILINGUAL DICTIONARY OF SOIL SCIENCE (DICCMCS)

The Multilingual Dictionary of Soil Science (DiccMCS), initially known as the Multilingual Glossary of Soil Science, is an international project initiated by the Spanish Society of Soil Science (SECS) and the Institute for Catalan Studies (IEC). It involves the participation of various societies and entities, including the Latin American Society of Soil Science, TERMCAT (Catalan Terminology Centre), TERMIGAL (Galician Service of

TABLE 2 | Soil science tree used in the multilingual dictionary of soil science (DiccMCS) and number of terms of each domain.

Domains or branches of DiccMCS	Number of terms
General concepts of the soil system	75
Origin of soil and soil organizations	3,500
Soil mineral components	1,100
Organic soil components	258
Physical properties and soil behaviour	1,300
Physicochemical and chemical properties and soil behaviour	770
Soil atmosphere and soil water	624
Biochemical, biological properties and soil ecology	423
Soil chemical fertility	1,231
Soil classification, taxonomy, and correlation	1,200
Soil information and spatial representation of the soil system	875
Soil quality, evaluation, degradation, and protection	1,063
Sustainable land use and management	700

Total number of terms: 7,000 (some terms belong to more than one branch).

Terminology) and the Royal Galician Academy (RAG), the Catalan Institution for Agrarian Studies (ICEA) and several universities and research centres.

The DiccMCS was promoted and directed by Jaume Porta, who conceived it as an original, synchronous, and online, open access terminological dictionary of Soil Science (Creative Commons CC BY NC license). At present it includes more than 7,000 entries. The four linguistic versions (Catalan, Spanish, Galician, Portuguese) are presented as independent dictionaries (Porta et al., 2017).

As promoter and co-author of the DiccMCS, Jaume Porta did not want to make a mere compilation task, but to do an in-depth analysis of the state-of-art of Soil Science. The DiccMCS had a precursor in the Multilingual Vocabulary of Soil Science (2010 online edition), authored by Jaume Porta and Rosa M. Poch, developed within the "CiT (Terminology of Sciences and Technology)" program of the Institute for Catalan Studies. This Vocabulary, in turn, traces its roots to the work published by the Polytechnic University of Catalonia back in 1989, titled "*Lèxic de la Ciència del Sòl*" (Porta et al., 1989). These works provided a terminological database as a starting point, gradually expanding as needed during the development. The Catalan version of the dictionary adheres to the new orthographic standards of the Institute for Catalan Studies.

Entries are categorized into branches (domains) of the Soil Science tree (**Table 2**), defined after consulting members of the Spanish Society of Soil Science on a voluntary basis. Contents are derived from primary sources (author criteria, manuals, doctoral theses, and scientific journals) and secondary sources (specialized glossaries and dictionaries). Thus, the DiccMCS is an original work with known authors. The content drafting began with the formulation of a preliminary definition for each entry, including corresponding linguistic equivalents. The review process involved submitting content for review in packages of eight entries (or octets) to multiple authors. This series of successive revisions by a minimum of three individuals allowed for the incorporation of suggested improvements, resulting in the final version of each entry (Porta et al., 2023).

The content is intended to achieve maximum objectivity, providing readers with elements to understand without difficulty. For instance, terms like "Soil Science" and "Pedology" in English correspond to the entry "*Edafología*," introduced by Emili Huguet de Villar, explaining the distinctions. This is also evident in entries related to different types of agriculture, latifundia, or terms associated with the environment and natural resources, fields with widely varying sensitivities. While achieving complete objectivity may not always be possible, the working methodology, involving successive revisions by different authors, contributed to reducing the impact of personal views in the DiccMCS. The DiccMCS is organized into articles, each consisting of an entry (monolexical or multilexical), the domain or domains it belongs to, content in the dictionary language, and equivalents in Spanish, French, Galician, English, Portuguese, and occasionally Basque. Entries are alphabetically ordered, although in the digital world and with web access, this is secondary. Homographic forms are followed by a numeric superscript to differentiate them.

The Catalan version coordination was led by Rosa M. Poch, member of SECS and IEC, alongside Jaume Porta. Equivalencies in Galician were coordinated by Eduardo García-Rodeja, a professor at the University of Santiago de Compostela and a member of SECS. Equivalencies in Portuguese were coordinated by Gonçalo Signorelli de Farias, former president of the Brazilian Society of Soil Science.

As coordinator of the project, Jaume Porta successfully integrated the work of individuals from over sixty institutions, serving as co-authors, specialty advisors, or coordinators for various languages. Additionally, he coordinated the linguistic revision, design development, and interface development, involving multiple institutions that make the DiccMCS possible.

At present (beginning 2024), while the Catalan and Spanish dictionaries are complete, the Galician and Portuguese ones are partly finished, partly in translation, with approximately 50% of the entries completed (**Table 3**). We hope that the institutions initially involved will allow this corpus of Soil Science to be completed soon, also as a tribute to its promoter.

ACTIVITY IN MEXICAN UNIVERSITIES. INTERNATIONAL SOIL SCIENCE COURSE, UNAM

Jaume Porta began his collaboration with the National Autonomous University of Mexico (UNAM) in 1980 as an invited Research-Professor to a Conference Cycle in the

TABLE 3 | Multilingual dictionary of soil science: links (Accessed January 15, 2024) and degree of completion.

Language	Link	Completion
Catalan	https://cit.iec.cat/DMCSC	100%
Galician	https://cit.iec.cat/DMCSG	Soil organic components, biological and biochemical properties, soil ecology, physical, physicochemical and chemical properties
Portuguese	https://cit.iec.cat/DMCSP	
Spanish	https://cit.iec.cat/DMCSE	100%

Agricultural Engineering career at the National School of Professional Studies (later Faculty of Higher Studies), Cuautitlán (UNAM). But it was only from 1993 that he started his activities as a regular invited professor in the International Soil Science Courses, starting from the XI International Soil Science Course, offered at the Autonomous University of Guerrero in 1993 (**Figure 7**). Simultaneously, he strengthened the teaching-research collaboration between Spain and Mexico through the UNAM as the founding venue for these courses coordinated by UNAM and *Consejo Superior de Investigaciones Científicas* of Spain (CSIC). The transformation into Diplomas occurred at the beginning of the millennium, promoted by both institutions. We must highlight his participation in eleven editions, up to the XXVI at the Autonomous University of Querétaro in 2008.

The book *Una oferta de educación a lo largo de toda la vida* (Porta et al., 2008), provides further information about these courses. In this book, the history of the course's inception is presented, along with the analysis of its academic approach, its evolution into a Diploma Courses, its potential, and externalities and its contribution to itinerant teaching and research, training professionals and postgraduates. At this point, he also proposed actions and solutions to decision-makers at local, national, and international level. In summary, it reflects Jaume Porta's tireless work in disseminating and promoting Soil Science in all its approaches.

The International Soil Science Courses and Diplomas, founded by Master Nicolás Aguilera, Emeritus Professor of UNAM and Doctor Honoris Causa of the Colegio de Postgraduados (CP), were created within the framework of the agreement between Mexico (UNAM) and Spain, serving as coordinating researchers of the CSIC from 1980 to 2009. The course was itinerant through some of the country's main universities. In the 11th edition of the International Soil Science Course, the collaboration of Jaume Porta at the Universidad Autónoma del Estado de Guerrero began (**Figure 7**). In its opening speech, Francisco Velasco de Pedro emphasised the threats to soil functioning in ecosystems and welcomed Jaume Porta. In six of these diploma courses Porta's wife, Marta López-Acevedo, also participated as a guest professor (**Figure 8**). Since joining as a lecturer in these courses, his contributions were not limited to lecturing, but also encompassed various collaborative actions in student training at the different universities hosting the courses, through specific mobility agreements with the UdL, from the final stage of undergraduate studies to the doctoral level. Simultaneously, he fostered the exchange of knowledge with participating academics, creating enduring bonds of friendship and collaboration.

JADE Program

Recognizing the reverence for jade in pre-Hispanic cultures, where knowledge was safeguarded and slowly released, this program was named to establish mobility agreements for high school and undergraduate students from the host universities of the Courses-Diplomas to undertake short-term bilateral stays starting from 2002. Sponsored by the University of Lleida-Santander Group-Mexican Universities, the notable participants included: Benemérita U. Autónoma de Puebla (BUAP), U. Autónoma Chapingo (UACh), U. Autónoma de Chiapas (UNACH), U. Autónoma de Nayarit (UAN), U. Autónoma del Estado de Hidalgo (UAEH), U. de Guadalajara (UdeG), U. Michoacana de San Nicolás de Hidalgo (UMICH): with 25 students benefiting from 2002 to 2007. Furthermore, collaboration was intensified with other countries in the Americas, such as the collaboration with the Soil Survey Service of the US (NRCS), the Conchita Badía Chair, and the Academic Choir of UNAM.

FIGURE 7 | Jaume Porta, Nicolás Aguilera and Francisco Velasco, in the opening ceremony of the XI International Soil Science Course 1993 (Photo by N. García).

FIGURE 8 | Jaume Porta and Marta López-Acevedo guest professors of the XXV CDIE in Soil Science, San Luís Potosí, 2007 (Photo by N. García).

The opinions and impressions of Mexican students and colleagues of Jaume Porta show the long-lasting impact that he left in Mexican Soil Science, to the point that during the celebration of the 47th Mexican Congress in Soil Science (October 2023), held at the Congress and Exhibition Centre of UNAM at Ciudad Universitaria, on behalf of the Organizing Committee, it was decided to honour his memory by naming room 2 "*Jaume Porta Casanellas*" in recognition of his lifelong dedication to Soil Science. His Mexican friends mostly remember the field trips visiting and describing profiles, or the completion of PhD programs and scientific stages thanks to the JADE Program. His friendship with Luis Hernández (Regional Director at USDA-NRCS, Amherst, Massachusetts) led him to collaborate on several projects, such as the Soil Map of Catalonia through several visits to Lleida to provide training in soil mapping using the USDA Soil Survey field guides. He also contributed to the Multilingual Dictionary of Soil Science and participated in field trips and courses in Catalonia, and especially recalls his fascination with talking about geo-politics and soil classification. Also, Mario Antonio Guevara Santamaría remembered how Porta's lectures stood out for their depth and clarity during the course. He seamlessly woven technical knowledge with philosophical insights, instilling in us a profound appreciation for the epistemology and transversality of Soil Science. His emphasis on viewing soil as a dynamic, interconnected system resonated deeply with us, setting the stage for a holistic approach to our future research. Moreover, he encouraged open dialogue and intellectual curiosity, fostering an environment where students felt empowered to explore and question. I distinctly remember engaging in lively discussions with him and other colleagues, exchanging ideas and insights that enriched our understanding of Soil Science. His wisdom, passion, and dedication continue to inspire us, serving as a guiding light in our pursuit of knowledge and understanding in the field.

WORK AS PRESIDENT OF THE SPANISH SOIL SCIENCE SOCIETY

In February 23, 2009, Jaume Porta was appointed President of the Spanish Society of Soil Science, position that he held until February 24, 2017 (SECS, 2024). Throughout those 8 years, his managerial experience, his excellence, and his great enthusiasm significantly energized a scientific society with over five hundred members and over 60 years of existence. At the beginning of his first term, the Strategic Guidelines of the SECS (2010–2020) were formalized, stemming from analyses, reflections, and debates held throughout 2009 within the framework of the Soil Science Encounters organized by Jaume Porta, which took place in Madrid, Murcia, Santiago de Compostela, and Granada. This project, coordinated by the SECS vice president at that time, Carmen D. Arbelo Rodríguez, involved the participation of over two hundred SECS members and resulted in a document that became the reference framework for future actions and decision-making within the SECS, translated into concrete initiatives through plans, programs, and projects.

During his presidency, various initiatives and projects were promoted and continue to be developed and consolidated: the Multilingual Dictionary of Soil Science [see *Jaume Porta's Contribution to the Multilingual Dictionary of Soil Science (DiccMCS)* section], the creation of the scientific journal Spanish Journal of Soil Science (see *His Role in the SJSS and Universia* section), the SECS Documentation Centre for Soil Sciences in Spain [see *SECS Soil Science Documentation Centre (Ce.SECS)* section], the TeSECS database of doctoral theses in Soil Science, the harmonization project of soil spatial information in the INSPIRE Directive, the white paper on soil treatment in compulsory secondary education and high school textbooks in Spain, the Spanish soil cartographic information program, INFORCAS.es, the commemoration of the 70th anniversary of the SECS, the celebration of World Soil Day and the 2015 International Year of Soils, the publication of the biannual online NEWS-SECS bulletin, among others (**Figure 9**).

Additionally, he continued to promote other aspects such as the annual SECS calendar with various soil-related themes, the reissue of the 1931 book "*El Suelo*" in homage to Emilio Huguet del Villar (SECS, 2017), the SECS award for Best Doctoral Thesis in Soil Science, the SECS award for the best research papers by high school students, participation in international soil profile description competitions for students, encouragement of soil presence in science museums, and the successive editions of the National Soil Meeting of the SECS (RENS), the National Symposium on Soil Degradation Control and Recovery (CONDEGRES), and the Iberian Congress of Soil Science (CICS). For many of the mentioned projects, Jaume Porta signed various agreements with different entities such as CSIC, the Royal Spanish Academy (RAE), the *Institut d'Estudis Catalans*, TERMCAT, the *Instituto Geográfico Nacional*, the *Centro Nacional de Información Geográfica*, the University of Lleida, the member societies of the Latin American Society of Soil Science, Banco Santander, and Universia. Likewise, he promoted the creation of the figure of the Corporate Member of the SECS, aimed at offering the opportunity for interaction between the SECS and entities (institutions, public and private centres and companies, such as TRACASA, the ICGC or EUROFINS) and thus establishing synergies in the professional field in the areas represented within the SECS. On the other hand, Jaume Porta enhanced the role of territorial delegations and sections of the SECS, providing them with individual budget allocations so they could carry out their activities.

For all his dedication to the SECS and his tireless work aimed at the dissemination of Soil Science in Spain and beyond our borders, Jaume Porta was appointed an honorary member of the SECS in 2018 and honorary president in 2019.

HIS ROLE IN THE SJSS AND UNIVERSIA

Upon assuming the presidency of the Spanish Society of Soil Science, Jaume Porta decided to undertake the project of remodelling the SECS scientific journal "*Edafología*" which inherited from other soil publications edited by the CSIC that

FIGURE 9 | NEWS-SECS cover of the information bulletin for SECS members created by Jaume Porta during his presidency of this society, corresponding to 2015, the international year of soils.

had successively changed names in recent decades. For this purpose, an advisory committee was established with members of the SECS, chaired by Tarsy Carballas Fernández, to issue a report (the "Carballas Report") on the future of the journal to adapt it to modern times. After various surveys and debates among committee members, several conclusions were presented. Among other aspects, it was noted the convenience of continuing to publish a journal sponsored by the SECS, preferably in electronic format, in English, with a quarterly periodicity, with rigorous peer review, guidelines for evaluation, thus becoming part of the Web of Science databases and being included in SCI, Scopus, and others, and fundamentally with original research content on various aspects of Soil Science. The need to internationalize the editorial board of the journal was also indicated, to outsource its editing and management, and to obtain external sponsorship for its financing.

With these premises and after several negotiations, at the end of 2010, Jaume Porta, as president of the SECS, signed an agreement with Universia, represented by its CEO, Jaume Pagès i Fita, and the CSIC, under the presidency of Rafael Rodrigo Montero, to manage this publication of the society with the new name of Spanish Journal of Soil Science (SJSS).

SJSS SPANISH JOURNAL OF SOIL SCIENCE • YEAR 2011 • ISSUE 1 • SPECIAL ISSUE

SJSS

SPANISH JOURNAL OF SOIL SCIENCE

1. MEASUREMENT OF SOIL AGGREGATE STABILITY USING LOW INTENSITY ULTRASONIC VIBRATION. Jasmin Schomakers, Axel Mentler, Nina Degischer, Winfried E.H. Blum & Herwig Mayer
2. APPLYING FREUNDLICH, LANGMUIR AND TEMKIM MODELS IN Cu AND Pb SOIL SORPTION EXPERIMENTS. Vega, F.A., Covelo, E.F. & Andrade, M.L.
3. SEASONAL CHANGES IN THE CARBOHYDRATE POOL OF AN ATLANTIC FOREST SOIL UNDER DIFFERENT VEGETATION TYPES. Martín A., Díaz-Raviña M. & Carballas T.
4. VARIABILIDAD ESPACIAL DE FERTILIDAD QUÍMICA DEL SUELO EN UN DISEÑO DE BLOQUE. Orden L., Mandolesi M.E., Kiessling R.J. y Ron M.M.
5. ARTIFICIAL CHINAMPAS SOILS OF MEXICO CITY: THEIR PROPERTIES AND SALINIZATION HAZARDS. Ramos Bello, R., García Calderón, N.E., Ortega Escobar, H.M. & Krasilnikov, P.
6. CHARACTERIZATION OF THE POTENTIAL MERCURY CONTAMINATION IN THE APOLOBAMBA GOLD MINING AREA, BOLIVIA. Acosta J.A., Martínez-Martínez S., Faz A., Millán R., Muñoz M.A., Terán T. & Vera R.
7. DPSIR ANALYSIS OF LAND AND SOIL DEGRADATION IN RESPONSE TO CHANGES IN LAND USE. Porta J. & Poch R.M.
8. LONG-TERM EFFECT OF NO-TILLAGE ON SOIL ORGANIC MATTER FRACTIONS IN RAINFED ARAGON (NE SPAIN). Blanco-Moure N., Gracia R., Bielsa A. & López M.V.

CSIC Consejo Superior de Investigaciones Científicas

SECS Sociedad Española de la Ciencia del Suelo

universia

FIGURE 10 | Cover page of the first issue of the Spanish Journal of Soil Science (2011).

Universia then took over the editing of the journal in electronic format, providing technical advice and exercising sponsorship to make the edition economically viable. For its part, the CSIC became part of the editorial board and the scientific committee, in addition to advising on the drafting of the internal regulations of the SJSS through its Publications Department. After the resolution of the contest convened by the SECS for the selection of the scientific director of the journal, Rosa M. Poch Claret was chosen, who proposed the appointment of Irene Ortiz Bernad as executive deputy director and Pedro Aranzadi (director of Universia Spain) as coordination deputy director.

After many efforts, on 15 November 2011, the first issue of the new electronic journal was published, and to give it more visibility, that first issue was also published in print and distributed to all members of the SECS, the presidencies of the Soil Science societies of Latin American countries, and other scientists from many parts of the world (**Figure 10**). From that moment on, the SJSS was published electronically on a quarterly

FIGURE 11 | The inauguration of the Centre, located in the library "Víctor López Seoane" of the Faculty of Biology of the USC took place on 7 July 2022 (International Soil Conservation Day) with the assistance of Jaume Porta and relatives of the donors. At the table, from left to right: Jaume Porta, Francisco Javier Salgado (Vice Dean, Faculty of Biology), Vicente Pérez-Muñuzuri (Vice Rector of Science Policy, USC), Jorge Mataix-Solera (President of the SECS), M^{a} Isabel Casal (Director of the BUSC) (Photo by Eduardo García-Rodeja).

basis under the auspices of Universia, peer-reviewed, and open access, with scientific works mainly in English and abstracts in Spanish, English, and Portuguese. This responded to the desire for the journal to be a vehicle for union and communication among university communities and other research centres in Spain, Portugal, Latin America, and the Caribbean dedicated to soil research, study, teaching, and management. In this regard, the scientific committee of the journal was mainly composed of highly esteemed soil scientists from countries in these areas.

Thus, the primary objective of the Spanish Journal of Soil Science was to publish original, innovative, and high-quality scientific works related to field and laboratory research in all basic and applied aspects of Soil Science, as well as interdisciplinary studies, short communications, and invited literature reviews related to soils from all countries and geographical areas. With this approach promoted by Jaume Porta, efforts were made to compile studies that were sometimes published in special issues derived from the offer to congress organizers to edit research papers presented at them and always meeting all the quality requirements of the SJSS: two issues with selected works from those presented at the 14th International Meeting on Soil Micromorphology of the IUSS, with Irina Kovda (Institute of Geography, Russian Academy of Sciences) and Curtis Monger (University of New Mexico) as guest editors and dedicated to micromorphologists Ulrich Babel and Nicolas Federoff; two issues with a selection of articles presented at the IV Iberian Congress of Soil Science, with María Teresa Barral Silva and Montserrat Díaz Raviña as guest editors; an issue with works presented at the VII Iberian Congress of Soil Science in 2016, with Manuela Abreu and Ana María Moliner as guest editors; and an issue with contributions to the 15th International Conference on Soil Micromorphology, held in Mexico in 2016, with Héctor Cabadas and Peter Kühn as guest editors and dedicated to Professor Georges Stoops on his 80th birthday.

From the beginning of the publication of the SJSS, international standards of scientific and editorial quality were scrupulously followed, in addition to having an audit process to ensure the quality of the English and Portuguese languages of the scientific articles. This bore deserved fruit, and since 2016, it has been indexed in many databases: Agricola, Directory of Open Access Journals (DOAJ), Ulrich's, Latindex, Redalyc, ICYT, Dialnet, Google Scholar, Academic Journals database, IUSS Soil Science Journals, GeoRef, InfoBase Index, Scopus, and Web of Science, with the editorial quality seal of FECYT. In addition, at the end of 2015, it was included in the Emerging Sources Citation Index (ESCI) of Clarivate Analytics, and currently, now edited by Frontiers, it already has an impact factor. This has been the result of the effort of many people, but undoubtedly the drive of Jaume Porta was decisive and essential to establish the Spanish Journal of Soil Science in the position it occupies today within the international scientific publishing space.

SECS SOIL SCIENCE DOCUMENTATION CENTRE (CE.SECS)

One of Jaume Porta's concerns was, for some time, the dispersion of information on soils, particularly of Spain; from this arose the idea of centralizing this information in an official centre that would facilitate its conservation and access to those interested in it.

The first step for the development of this initiative, assumed by the Spanish Society of Soil Science (SECS) when Jaume Porta was Honorary President, was an attempt to sign an agreement with the Geological and Mining Institute of Spain in 2017 to be a repository of old and current maps. Since it was not possible, in June 2018, the then president of the SECS, Jorge Mataix Solera, asked the Conference of Rectors of Spanish Universities (CRUE) to identify public universities that might be interested in hosting this centre, a request that was accompanied by a document with the proposal for its creation.

In the above-mentioned documents, the reasons that lead the Spanish Society of Soil Science to propose the creation of the Soil Science Documentation Centre are stated. The aim is to create a reference centre, located in a Spanish public university, which will be the recipient and responsible for the custody, cataloguing and management of all the documentation accepted, donated by Spanish research centres and universities and individuals, natural and legal, who have developed their professional activity in this field. The need for its creation is justified by 1) the current impossibility of being able to channel donations of Soil Science documentation to an efficient and safe final destination, 2) the interest in preserving such documentation in a catalogued and easily accessible form, which will improve the efficiency of public management of this type of documentation, and 3) the objective of satisfying the information needs of all interested groups, which should allow changing the current scenario in the access to Soil Science documentation in Spain.

In December 2018 the University of Santiago de Compostela (USC), at the request of the Department of Soil Science and Agricultural Chemistry, submitted to the SECS its proposal to host the centre, which in February 2019 was awarded to USC.

On 4 October 2019, the "Agreement between USC and SECS for the creation and management of the SECS Centre for Soil Science Documentation at USC" was signed (**Figure 11**). According to the aforementioned agreement, the centre aims to have a space in which a paper copy of the main works related to Soil Science is kept and its functions are to be the recipient of disinterested modal donations of documentation concerning Soil Science that the SECS obtains or processes and to efficiently manage the documentation of each donation (computerized cataloguing, preservation of documents and accessibility to such documentation). At present, the centre has more than a thousand monographs, twelve titles of scientific journals, doctoral theses (141), reports for different administrations (82), maps, among other contributions coming mainly from the donations of Carlos Roquero de Laburu (31 January 2020), Mariano Magister Hafner (10 March 2020), Jaume Porta Casanellas (23 December 2021) and, recently, Jorge Mataix Beneyto (19 February 2023).

Among the documentation, due to its historical value, it is worth mentioning the donation by Jaume Porta of the correspondence between Emilio Huguet del Villar and various CSIC officers between 1948 and 1949.

CONCLUDING REMARK

Jaume Porta stands as a rare individual whose contributions as a soil scientist and university manager have had a profound impact. His contributions to research and education have significatively improved our understanding of Soil Science and have resulted in the growth of several generations of soil scientists. Porta's dedication and vision show how one person's efforts can lead to significant positive changes to shape a better world.

AUTHOR CONTRIBUTIONS

The alphabetical order of the authors indicates an equal contribution, without meaning greater relevance or prevalence of any of them. Given the nature of this article as a tribute to Jaume Porta, the authors' participation has been voluntary, trying to reflect the personal and professional relationship we had with him. All authors listed have made a substantial, direct, and intellectual contribution to the work and approved it for publication.

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CONFLICT OF INTEREST

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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REFERENCES

Andreu-Gasa, M., and Villar-Mir, C. (2018). El Consell Social de la UdL: 25 Anys Acompanyant la Universitat de Lleida. Edicions de la Universitat de Lleida. ISBN: 8491440917.

Baize, D. (2000). *Guide des analyses en pédologie.* Paris: INRA. ISBN: 2-7380-0892-5.

Benedito, J., and Benedito, M. (2001). *Universitat, Arquitectura i Territori. Departament d'Universitats, Recerca i Societat de la Informació*. Barcelona: Generalitat de Catalunya.

Boixadera, J., and Porta, J. (1991). *Información de Suelos y Evaluación Catastral – Método del Valor Índice*. Madrid (Spain): Centro de Gestión Catastral y Cooperación Tributaria. ISBN 8487505935X.

Casby-Horton, S., Herrero, J., and Rolong, N. A. (2015). Gypsum Soils: Their Morphology, Classification, Function, and Landscapes. *Adv. Agron.* 130, 231–290. doi:10.1016/bs.agron.2014.10.002

Comisión del Banco de Datos de Suelos y Aguas (CBDSA) (1983). *SINEDARES, Manual para la Descripción Codificada de Suelos en el Campo*. Madrid: Ministerio de Agricultura, Pesca y Alimentación de España. ISBN: 84-7479-226-6.

Cornadó, M. P., and Porta, P. (2007). *Alvaro Siza a la Universitat de Lleida*. Lleida: Estudi Nix, Edicions de la Universitat de Lleida.

FAO (1976). *A Framework for Land Evaluation. Soils Bulletin 32.* Rome: Food and Agriculture Organization of the United Nations. FAO editions.

FAO (2020). *Red Mundial de Laboratorios de Análisis de Suelos, GLOSOLAN.* Roma: Food and Agriculture Organization of the United Nations. FAO editions.

Herrero, C., Boixadera, J., Danés, R., and Villar, J. M. (1993). *Mapa de Sòls de Catalunya 1: 25,000 Bellvís 360-1-2 (65-28)*. Barcelona: Direcció General de Producció i Indústries Agroalimentàries, i lnstitut Cartogràfic de Catalunya.

Herrero, J., and Porta, J. (2000). The Terminology and the Concepts of Gypsum-Rich Soils. *Geoderma* 96 (1-2), 47–61. doi:10.1016/S0016-7061(00)00003-3

Herrero, J., Porta, J., and Fedoroff, N. (1992). Hypergypsic Soil Micromorphology and Landscape Relationships in Northeastern Spain. *Soil Sci. Soc. Am. J.* 56 (4), 1188–1194. doi:10.2136/sssaj1992.03615995005600040031x

Herrero, J., Rodríguez, R., and Porta, J. (1989). *Colmatación de Drenes en Suelos Afectados por Salinidad: Finca Experimental de San Juan de Flumen (Huesca).* Zaragoza (Spain): Instituto Fernando el Católico. Available at: https://ifc.dpz.es/publicaciones/ebooks/id/1582 (Accessed September 30, 2024).

ICEA (Institució Catalana d'Estudis Agraris) (2024). Institució Catalana d'Estudis Agraris. Available at: https://icea.iec.cat/ (Accessed March 15, 2024).

ICGC (Institut Cartogràfic i Geològic de Catalunya) (2019). *Mapa de Sòls de Catalunya Soil Taxonomy 1:250,000*. Barcelona (Spain): Institut Cartogràfic i Geològic de Catalunya. ISBN 978-84-393-9836-3.

Jarauta, E. (1989). *Modelos Matemáticos del Régimen de Humedad de los Suelos. Aplicación a la Determinación del Régimen de Humedad de los Suelos del Área Meridional de Lleida*. Barcelona (Spain): PhD, UPC, Departament de Matemàtica Aplicada III. ISBN 846898230X. doi:10.5821/dissertation-2117-94025

Jarauta, E., Porta, J., and Boixadera, J. (1989). *Règims d'Humitat dels Sòls: Interès i Problemàtica en l'Aplicació als sòls de Catalunya*. Barcelona: Butlletí de la Institució Catalana d'Història Natural, 87–96.

MAPA (Ministerio de Agricultura, Pesca y Alimentación) (1986). Métodos oficiales de análisis. Madrid: Tomo III. ISBN-84-7479-532-X.

Martínez-Casasnovas, J. A., and Porta, J. (1999). "Tecnologías de la Información Espacial (Fotointerpretación y SIG) en el Análisis de los Procesos de Erosión por Cárcavas y Barrancos en el Alt Penedès – Anoia (Cataluña)," in *Libro Homenaje a D. Ángel Ramos Fernández (1926 – 1998).* Editor S. González-Alonso (Madrid: Real Academia de las Ciencias Exactas, Físicas y Naturales, Academia de la Ingeniería y ETSIM – UPM), 465–482. ISBN: 84-87125-425.

Poch, R. M. (1992). *Fabric and Physical Properties of Soils with Gypsic and Hypergypsic Horizons of the Ebro Valley*. PhD. Thesis. Belgium: Univ. of Ghent.

Porta, J. (1974). *Proyecto de Unidad Centralizada para Análisis Automático de Suelos*. Spain: Ministerio de Agricultura.

Porta, J. (1975). *Redistribuciones Iónicas en Suelos Salinos, Influencia Sobre la Vegetación Halófila y las Posibilidades de Recuperación de los Suelos con Horizonte Gypsico y otros Suelos Halomorfos de las Márgenes del río Gigüela*. Tesis doctoral. Madrid: Escuela Técnica Superior de Ingenieros Agrónomos, UPM, 259.

Porta, J. (1996). *Una Commemoració: Un Temps per la Reflexió*. Editor J. J. Busqueta 700 Aniversari. Universitat de Lleida. Edicions de la Universitat de Lleida.

Porta, J. (1997). "Introducció. Les biblioteques imaginàries de la Universitat de Lleida," in *Llibre de les biblioteques imaginàries de la Universitat de Lleida*. Editors A. Bustamante and J. J. Busqueta (Lleida: Fundació 700 Aniversari. Edicions de la Universitat de Lleida).

Porta, J. (1998). Methodologies for the Analysis and Characterization of Gypsum in Soils: A Review. *Geoderma* 87 (1-2), 31–46. doi:10.1016/S0016-7061(98)00067-6

Porta, J. (2001). "Un patrimoni perdut, una ferma voluntat de reconstrucció," in *Patrimoni d'obra artística de la Universitat de Lleida*. Editor F. Vilà (Lleida: Edicions de la Universitat de Lleida).

Porta, J. (2003). *Doctorat Honoris Causa a l'exili català per la Universitat de Lleida*. Lleida: Edicions de la Universitat de Lleida.

Porta, J. (2005). *Descobrir Lleida. Passejant per l'Arquitectura del Segle XX. March editor*. Spain: Vallbona de les Monges (Lleida). ISBN: 9788495608918.

Porta, J. (2009). Quantification of Land Degradation Stress: An Overview. Reiskirchen: Catena Verlag. *Adv. Geoecol.* 40, 163176.

Porta, J., Alcañiz, J. M., Castells, E., Cruañas, R., Danés, R., Felipó, M. T., et al. (1987). *Introducció al Coneixement del sòl: Sòls del Països Catalans (separated edition of Vol. 3: Història Natural dels Països Catalans).* Barcelona: Col·legi Enginyers Agrònoms de Catalunya -Fundació Enciclopèdia Catalana. ISBN 84-398-8658-6.

Porta, J., Ballesta, A., and Martín-Sánchez, J. A. (2013). *L'Escola Tècnica Superior d'Enginyeria Agrària de Lleida 1972-2012: Un valor al servei de la societat*. Lleida: Fundació publica Institut d'Estudis Ilerdencs.

Porta, J., Castroviejo, S., and López-Acevedo, M. (1980). "Diagnosis of Salinization and Alkalinization Levels in Spanish Salt-Affected Soils by Means of Halophytic Community Studies," in International Symposium of Salt-Affected Soils, Karnal (India), February 8–21, 1980, 39–47.

Porta, J., Ferret, M., Teixidor, N., and Poch, R. M. (1989). *Lèxic de la Ciència del Sòl, Català/Castellà/Francès/Anglès*. Barcelona: Universitat Politècnica de Catalunya, 115. ISBN 84 7653 038 2.

Porta, J., García-Calderón, N., López-Acevedo, M., and Almendros, G. (2008). *Una Oferta de Educación a lo Largo de Toda la Vida. Análisis de 25 Ediciones del Curso Internacional de Edafología Nicolás Aguilera de la UNAM*. Madrid: Ediciones Mundi-Prensa, 137. ISBN: 978-968-7462-58-5.

Porta, J., and Herrero, J. (1990). Micromorphology and Genesis of Soils Enriched with Gypsum. *Dev. Soil Sci.* 19 (C), 321–339. doi:10.1016/S0166-2481(08)70344-1

Porta, J., and Herrero, J. (1996). "Vulnerability of Soils under Irrigation," in *Sustainability of Irrigated Agriculture. NATO Science Series E: Applied Sciences*. Editors L. S. Pereira, R. A. Feddes, J. R. Gilley, and B. Lesaffre (Dordrecht: Springer), 312, 85–96. doi:10.1007/978-94-015-8700-6_6

Porta, J., Herrero, J., and Latorre, S. (1986a). "Evaluación de Suelos Para Riego: Criterios y Problemática en los Regadíos de Huesca," in *Salinidad en los Suelos: Aspectos de su Incidencia en Regadíos de Huesca*. Editor J. Herrero (Zaragoza, Spain: Diputación General de Aragón), 119–146. ISBN 8450549485.

Porta, J., and Julià, R. (1983). *Els sòls de Catalunya: Àrea meridional de Lleida*. Barcelona (Spain): Departament d'Agricultura, Ramaderia i Pesca de la Generalitat de Catalunya, 332.

Porta, J., and Lladonosa, M. (1998). *La Universidad en el cambio de siglo*. Madrid: Fundación 700 Aniversario de la Universidad de Lleida y Alianza Editorial.

Porta, J., and López-Acevedo, M. (2005). *Agenda de Campo de Suelos. Información de Suelos Para la Agricultura y el Medio Ambiente*. Mundi Prensa Libros, 541. ISBN 84-8476-231-9

Porta, J., López-Acevedo, M., and Rodríguez-Ochoa, R. (1986b). *Técnicas y Experimentos en Edafología, Col·legi Oficial d'Enginyers Agrònoms de Catalunya*. Barcelona, Spain. ISBN 84-600-4341-X.

Porta, J., López-Acevedo, M., and Roquero de Laburu, C. (1994). *Edafología para la Agricultura y el Medio Ambiente*. Madrid: Ediciones Mundi-Prensa. ISBN: 84-8476-148-7.

Porta, J., López-Acevedo, M., and Roquero de Laburu, C. (2003). *Edafología: Para la Agricultura y el Medio Ambiente*. Mundi Prensa Libros, 1994 ISBN: 84-7114-468-9; 1999 (2nd Ed.). ISBN 84-7114-784-X; 2003 (3rd Ed.) ISBN: 84-8476-148-7

Porta, J., López-Acevedo, M., and Poch, R. M. (2009). *Introducció a l'Edafologia. Ús i Protecció de Sòls*. Mundi-Prensa, 507. ISBN: 978-84-8476-385-7

Porta, J., López-Acevedo, M., and Poch, R. M. (2010). *Introducción a la Edafología. Uso y protección del suelo*. Mundi-Prensa, 2008, ISBN: 978-84-8476-342-0; 2nd Ed. 2010, ISBN: 978-84-8476-405-2

Porta, J., López-Acevedo, M., and Poch, R. M. (2019). *Edafología. Uso y protección de suelos*. Ed. Paraninfo 3rd ed. ISBN: 978-84-8476-661-2; 4th Ed. ISBN: 978-84-8476-750-3

Porta, J., López-Acevedo, M., and Rodríguez-Ochoa, R. (1986c). *Técnicas y Experimentos en Edafología*. Barcelona, Spain: Col·legi Oficial d'Enginyers Agrònoms de Catalunya. ISBN 84-600-4341-X

Porta, J., Mestres, J. M., and García-Rodeja, E. (2017). "Plurilingüismo Edafológico de la Península Ibérica: El Diccionario Multilingüe de la Ciencia del Suelo de la SECS," in *Libro de Resúmenes XXXI Reunión Nacional de Suelos*, 8–9. Madrid, 6-9 de Junio de 2017.

Porta, J., and Poch, R. M. (2011). DPSIR Analysis of Land and Soil Degradation in Response to Changes in Land Use. *Span. J. Soil Sci.* 1 (1), 100–115. doi:10.3232/SJSS.2011.V1.N1.07

Porta, J., Poch, R. M., and Boixadera, J. (1988). "Land Evaluation and Erosion Control Practices on Mined Soils in NE Spain," in *Soil Erosion Protection Measures in Europe: Proceedings of the European Community Workshop on Soil Erosion Protection*. Editors U. Schwertmann, R. J. Rickson, and K. Auerswald (Freising, Germany: E. Schweizerbartsche Verlagsbuchhandlung), 189–206. ISBN 9783510653843.

Porta, J., and Ramos, M. C. (1993). Erosió Hídrica en Vinya per a Producció de vi d'Alta Qualitat en Zona Mediterrània (Anoia-Penedès): Quantificació de les Pèrdues de Nutrients per Erosió del sòl i Implicacions. *Quaderns Agraris* 16, 5–19.

Porta, J., Rodríguez-Ochoa, R., and López-Acevedo, M. (1993). *Laboratori d'Edafologia*. Universitat Politècnica de Catalunya. ISBN 84-7653-252-0

Porta, J., Serra, E., Aran, M., and Masalles, R. M. (1983). Projecte de Rehabilitació de Sòls a l'Explotació a cel Obert de Coll de Pradell. Carbones de Berga S.A. Technical Report.

Porta, J., Torras, J., and Torrents, X. (2023). *Cómo se elabora un diccionario: caso del Diccionario Multilingüe de la Ciencia del Suelo*. Editor J. Arricibita, et al. (Pamplona/Iruña: Libro de Resúmenes de la XXXIII Reunión Nacional de Suelos), 122–123.

Porta, J., and Villar, J. M. (1987). *Proyecto de Laboratorio de Fertilidad de Suelos en la Partida de La Caparrella (Lleida)*. Universitat Politècnica de Catalunya. Escola Tècnica Superior d'Enginyers Agrònoms de Lleida. Diputación de Lleida. Lleida.

Porta-Casanellas, J. (1985). Taxonomia Comparada de Sòls: Perspectives per a Catalunya. *Butll. Inst. Cat. Hist. Nat.* 50, 229–239.

Porta, J., and Villanueva, D. (2012). Formación de Neologismos en Ciencia del Suelo. *Span. J. Soil Sci.* 2 (2), p. 90-103.

Ramos, M. C., and Porta, J. (1994). Rainfall Intensity and Erosive Potentiality in the NE Spain Mediterranean Area - 1st Results on Sustainability of Vineyards. *Nuovo Cimento della Societa Italiana di Fisica C-Geophysics and Space Physics* 17 (3), 291–299.

Ramos, M. C., and Porta, J. (1997). Analysis of Design Criteria for Vineyard Terraces in the Mediterranean Area of Northeast Spain. *Soil Technol.* 10 (2), 155–166. doi:10.1016/S0933-3630(96)00006-2

Rodríguez, R., Herrero, J., and Porta, J. (1990). Micromorphological Assessment of Drain Siltation Risk Indexes in a Saline-Sodic Soil in Monegros Irrigation District (Spain). *Dev. Soil Sci.* 19 (C), 41–52. doi:10.1016/s0166-2481(08)70314-3

Roquero, C., and Porta, J. (1979). *Agenda de campo para estudio del suelo*. Madrid: Universidad Politécnica de Madrid.

Roquero de Laburu, C., and Porta, J. (1995). *Agenda de campo para el estudio del suelo*. Universidad Politécnica de Madrid, 1979 (2nd Ed.). ISBN 84-7401-058-6; 1995 (7th Ed.). ISBN 84-7401-058-6

Secció de Sòls de la ICEA (2024). ICEA – Secció Sòls. Available at: https://icea.iec.cat/seccions/sols// (Accessed March 15, 2024).

SECS (Sociedad Española de la Ciencia del Suelo) (2017). *Homenaje a Emilio Huguet del Villar en el Octogésimo Aniversario de la publicación de "Los suelos de la Península Luso-Ibérica"*. Madrid: Sociedad Española de la Ciencia del Suelo, 288.

SECS (Sociedad Española de la Ciencia del Suelo) (2024). Available at: https://www.secs.com.es// (Accessed March 28, 2024).

Soil Survey Staff (SSS) (1975). in *Agricultural Handbook* (Washington DC: U.S. Department of Agriculture, Soil Conservation Service), 436.*Soil Taxonomy: A Basic System of Soil Classification for Making and Interpreting Soil Surveys*

Villar, P., and Aran, M. (2008). *Guia d'Interpretació d'Anàlisis de sòls i Plantes*, 2008. Lleida: Departament d'Agricultura, Alimentació i Acció Rural i Consell Català de la Producció Integrada.

ORIGINAL RESEARCH
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The Efficacy of Organic Amendments on Maize Productivity, Soil Properties and Active Fractions of Soil Carbon in Organic-Matter Deficient Soil

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The decline in soil productivity due to intensive cultivation, unbalanced fertilization and climate change are key challenges to future food security. There is no significant research conducted on the effect of organic amendments on soil properties and active carbon fractions in organic-matter deficient soils under changing climate. Biochar (BC) is a stabilized organic amendment produced from organic materials and is increasingly recognized as being able to improve soil health and crop productivity. The present study was conducted to determine the efficacy of compost (CM) (0.5%, 1%) (w/w) and animal manure (AM) (0.5%, 1%) (w/w) alone and combined with 3% (w/w) biochar, on soil carbon fractions, soil properties, and crop growth in a low-fertile soil. The results revealed significant increased 46% plant height, 106% and 114% fresh and dry shoot weight respectively, and 1,000-grain weight increased up to 40% when 3% BC with 1% CM was applied, compared to a control. Similarly, substantial increases in 69% soil organic matter, and 70% carbon pool index were observed at 3% BC, and under 3% BC with 1% CM increased 11% microbial biomass carbon compared to the control. Overall, the results suggest that 3% BC addition along with 1% CM and AM (1%) had greater potential to improve the soil carbon pool, microbial biomass, and soil health, all of which will ultimately enhance maize yield when grown in low-fertility soil. The application of BC, CM, and AM are a viable green approach, that not only boosts crop yields and improves soil properties and but also contributes to a circular economy.

Keywords: biochar, labile carbon, microbial biomass carbon, soil health, crop production

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INTRODUCTION

Soil is a non-renewable resource that performs a vital role in ecosystem services and acts as a medium for plant growth by providing essential nutrients, water, gaseous exchange, and as an environmental buffer, facilitating degradation and the reduction of natural and xenobiotic toxic substances (Amoakwah et al., 2020). Intensive cultivation, together with injudicious fertilization and poor cropping practices, results in declining soil health and crop productivity, thereby threatening future food security (Naeem et al., 2018). This situation is further accelerated due to soil erosion, salinization, and desertification, which leads to soil organic carbon loss, loss of microbial biodiversity and, ultimately, loss of crop productivity (Gregory et al., 2015). Similarly, poor management practices, such as indiscriminate ploughing and burning or the complete removal of crop residues, will further worsen soil organic matter (SOM) degradation and deteriorate soil quality (Lal, 2015). The loss of SOM through microbial degradation depletes the organic carbon pool, microbial biodiversity, and increases greenhouse gases (GHG) emissions (Shakoor et al., 2020). This situation demands more suitable strategies to help ensure sustained soil health and crop production in an eco-friendly manner. Synthetic fertilizers are used to boost crop yields, but the continuous use of these fertilizers will lead to soil degradation and the contamination of water bodies, which is another significant concern (Haider et al., 2021). Low organic-matter content in calcareous soils leads to lower nutrient availability and the loss of biological activity. Soil quality can be restored through proper management practices that enhance SOM content and improve microbial biodiversity and soil properties, thereby improving its productivity (Shakoor et al., 2020; Haider et al., 2021). It has been established that the addition of organic amendments to soil resulted in a higher SOM content, which serves as the storehouse for many other plant nutrients (Srivastava et al., 2020). Labile organic carbon (LOC) is highly active part of SOM that decomposes abruptly after its application to soil and is vital to the soil food web (Adnan et al., 2020). It is well known that the direct addition of organic amendments (OAs) increases organic carbon (OC) stock, provides food to microbial communities, increases nutrient (nitrogen, potassium, phosphorus, calcium, and magnesium) availability, prevents erosion, improves soil aeration and soil structure, and decreases soil crusting and bulk density (Obalum et al., 2017).

Traditionally, animal manure (AM), mulches, and other organic wastes re-used as soil conditioners, and have been recognized as effective means for improving nutrient supplies to crops and microbial activity in soils (Kamara et al., 2015). The AM is a rich consortium of plant-available nutrients, that reduce bulk density, and improve soil aeration, aggregate stability, crop production, and organic carbon reserve in soil but also affects GHGs emissions (Zhou et al., 2017). However, there are some drawbacks associated with the direct application of these OAs including, but not limited to, fast decomposition and quick release of nutrients, which results in nutrient leaching and contributes to eutrophication and GHG emissions (Sutton et al., 2014; Urra et al., 2019). Composting is another technique in which organic waste (plant leaves and twigs, food scraps, manure or sewage) is converted into a stable form and remains in the soil for a period of time than untreated organic wastes and compost application to soil improves nutrient availability, aeration, and reduced bulk density, and thus enhances soil structure but it also contains heavy metals (Al-Omran et al., 2019; Niamat et al., 2019). Because of the usage of animal wastes, biowastes, and biosolids used in composting can include metals and antibiotics. Compost, biosolids, and biowastes are used as soil amendments, and long-term usage of these products may result in heavy metals build-up in soil and antibiotic resistant in the environment (Arya et al., 2021; Peng et al., 2021) which may contaminate soil and water bodies through runoff and leaching, thus limiting the long-term use of compost (Lillenberg et al., 2010). Therefore, these raw organic materials must first be processed before direct application to soil, and the conversion of readily decomposed AOs into BC is another attractive alternative approach for addressing these challenges (Rahman et al., 2020).

Biochar (BC) is a black carbonaceous material produced through pyrolysis, which is the thermal decomposition of organic materials in the absence of oxygen (Zhang et al., 2019). In this regard, a variety of feedstock, such as agricultural wastes (tree leaves, twigs, bark, straw, bagasse, husks, nutshells, corncob, and corn stalks etc.), animal and bird waste (animal beds and manure), industrial waste (bagasse and grain) have been extensively used for BC production (Novotny et al., 2015; Azeem et al., 2020; Naveed et al., 2020). In recent decades, the application of BC to combat low soil fertility and climate change has aroused the interest of many scientists due to its ability to improve soil health, bio-energy generation, carbon sequestration, and the immobilization of inorganic and organic pollutants (Rehman et al., 2016). The addition of BC to soil also improves soil water and nutrient retention capacity, soil aeration and soil structure, and enhances nutrient availability to plants, which ultimately increases plant growth and yield (Singh et al., 2019). Moreover, the incorporation of BC into soil positively impacts carbon sequestration, reduces greenhouse gas (GHG) emissions, and increases carbon pools by altering microbial community composition and providing substrates to microbes, and resistant to decomposition (Hui, 2021). Its porous nature and large surface area provide habitats to soil microbes under stress, as the ash content in BC delivers nutrients to plants and microbes (Kocsis et al., 2022). Combing BC with CM not only improve composting efficiency and end-product quality and stabilize nutrient release from CM or AM from long time, but also increased BC surface area and retain nutrient release (Rivelli and Libutti, 2022). Application of such amendments in calcareous soils not only improve soil properties and nutrient availability but also significantly enhances organic carbon in soil (Abrar et al., 2020). Moreover, the recalcitrance nature of BC and its long-term soil stability are its main advantages over other OAs (Nguyen et al., 2018). In previous studies, several authors only tested the application effects of BC, CM or AM on crop growth and soil health. However, few researchers have investigated the impact of combined application of BC, CM or AM on crop growth and yield in nutrient-depleted soils (Lashari et al., 2015; Sánchez-García et al., 2016; Singh et al., 2019; Abbas et al., 2020; Pandit et al., 2020).

There are various areas where research on OAs requires further exploration, and the major knowledge gap regarding the combined impacts and application rates of BC, CM, and AM on active soil components and the carbon management index. We hypothesized that BC application CM or AM will increase the active portions of soil carbon, including microbial biomass carbon (MBC) and total carbon (TC) contents in organic-matter deficient soil. This is because different OA have different rates of decomposition and nutrient release, and by combining it could lead to a more sustained improvement in soil properties over time. Additionally, more research is needed for long time effects of these amendments on soil properties in organic-matter deficient soil. The current study especially aims to evaluate the cumulative impacts of BC, CM, and AM on maize productivity, nutrient absorption, soil properties, and the carbon management index under organic matter deficient soil.

MATERIALS AND METHODS

Biochar and Compost Preparation and Characterisation

Corncob biochar (BC) was prepared from corncob feedstock at 350℃ using muffle furnace (Gallon Hop, England). Feedstock was filled in pyrex flask having 2 L capacity and bear temperature up to 1,000°C. Silicon grease was used to prevent oxygen entering the flask, and the flask outlet was attached to a bended glass rod to remove water vapours and gasses from the furnace and work area. Feedstocks were collected from the agronomy research field at the University of Agriculture, Faisalabad (UAF), washed to remove dust and other impurities, sun-dried to remove moisture, and crushed into 2–5 mm sized particles for biochar preparation. Sánchez et al. (2009) described procedure was followed for biochar preparation. During pyrolysis, furnace temperature was gradually increased by 15℃ $\min^{-1}$ and 30-min residence time was adjusted after attaining a maximum temperature of 350℃. The furnace was then allowed to cool until the temperature dropped to 20℃. After that the lid was removed and prepared BC was collected and stored in plastic bag for further analysis.

Animal manure was collected from the animal husbandry farm of UAF, Pakistan. The collected AM was then dried, crushed, and stored for future use. The compost was prepared from vegetables and fruit waste in a locally fabricated composter unit. The fruit and vegetable waste were collected from a local market and sun-dried to remove extra moisture, unwanted stones, and plastic materials and oven dried for 24 h to reduce the water content by up to 15% and then crushed with a grinder. The ground material was transferred to the composter for compost preparation. For proper composting, a 40% moisture level was constantly maintained, and the composter was rotated at 50 rpm until an odourless dark-brown colour compost was obtained (Naveed et al., 2021).

The physiochemical properties of OAs were shown in (**Table 1**). Electrical conductivity (EC) and pH were measured using a soil: water (1:20) suspension (Abbas et al., 2020; Naveed et al., 2021). The NH_4-acetate method was used for determination of cation exchange capacity (CEC) (Gaskin et al., 2010), total organic carbon was determined using a total organic carbon (TOC) analyser [TRL-TOC, Turkey] (Aziz et al., 2021). Wet digestion method was used for N, P, and K in which 0.5 g of sample was digested with 10 mL H_2SO_4 and add 2 mL H_2O_2 and heated till clears solution was obtained (Wolf, 1982). After digestion, the samples were stored for testing. The total nitrogen was measured using the Kjeldahl method and the flame photometer (PFP7, Jenway, Essex, UK) was used to calculate K, while the spectrophotometer (UV-1201, Shimadzu, Tokyo, Japan) was utilized to assess P using the vanadate-molybdate procedure following ICARDA, 2013 (Estefan et al., 2013).

Experimental Design

A pot study was conducted at Soil Science Research Station, University of Agriculture Faisalabad in a wire house under natural conditions. For this purpose, the soil was collected from the Soil Science research field (31.439082° N, 73.069365° E) and sieved with a 2 mm sieve to remove plant roots, stones, and other unwanted particles. The soil was homogenized, and 30 plastic pots (width 1.5 ft., height 2.5 ft.) were filled with soil, and each pot contained 18 kg soil and recommended NPK (220:160:120 kg ha^{-1}) fertilizers were mixed into the soil, comprising urea, diammonium phosphate, and sulphate of potash. Ten different treatments; T_0 (CK): control; T_1 (CM-0.5): compost 0.5%; T_2 (CM-1): CM 1%; T_3 (BC-3): BC 3%; T_4 (BC-3+CM-0.5): BC 3% + CM 0.5%; T_5 (BC-3+CM-1): BC 3% + CM 1%; T_6 (AM-0.5): AM 0.5%; T_7 (AM-1): AM 1%; T_8 (BC-3+AM-0.5): BC 3% + AM 0.5%; and T_9 (BC-3+AM-1): BC 3% + AM 1% were applied under completely randomized design (CRD) with three replications of each treatment. Maize (variety FH-1046) was obtained from the Maize Research Station, Ayyub Agricultural Research Institute, Faisalabad, Pakistan, and used as a test crop and 4 seeds were sown in each pot at field capacity. Pots were kept under polythene sheet covered wire house to prevent rain and animal attack. The pots were watered with water bucket as needed during the entire growth period.

Soil Analysis

After soil homogenisation, soil samples were collected in plastic bags for basic soil analysis. Soil pH was measured with a pH meter (JENCO Model- 671 p) after making saturated soil paste (Schofield and Taylor, 1955). Soil texture was determined using the hydrometer method (Bouyoucos, 1962). Soil moisture contents, CEC and extractable K were measured using standard procedure (United States Salinity Laboratory Staff. 1954). Walkley, (1947) described method was used for SOM determination in which 1 g of soil mixed with 5 mL $K_2Cr_2O_7$ and 10 mL H_2SO_4 was added and allowed the flask to stand for 30 min to cool and add 100–150 mL distilled water. After that 3 mL of orthophosphoric acid (H_3PO_4), 5–10 drops of indicator, and titrate it against standardized ferrous sulphate to bright green endpoint. Total N was measured using Kjeldahl method (Bremner, 2016), and exchangeable P was measured in which 2.5 g of soil was treated with 0.5 M $NaHCO_3$ extracting solution and shake for 30 min and filtration. Pipette out a 5 mL aliquot in a 25-mL volumetric flask, and 5 mL of colour development reagent. The intensity of the blue colour is measured with 880 nm wavelength using spectrophotometer (Olsen et al., 1954).

Agronomic Parameters

The maize was harvested at zodiac stage (R_6). To assess maize growth and yield, plant height and cob length were recorded using scale, shoot fresh biomass after harvest and dry biomass and total grain weight were weighted using weighing balance.

Measurement of Physiological Parameters

Infrared gas analyzer (IRGA, LCA-4, ADC, Hoddesdon, UK) was used for physiological parameters measurement. Photosynthetic rate, transpiration rate (Tr), water use efficiency (WUE) and stomatal conductance (SC) (Ben-Asher et al., 2006). The SPAD-

TABLE 1 | Characterization of soil, CM, BC, and AM used in the experiment.

Characteristics	Units	Soil	CM	BC (350°C)	AM
pH		7.94 ± 0.02	7.53 ± 0.01	6.97 ± 0.01	8.0 ± 0.06
EC	dS m^{-1}	1.12 ± 0.02	3.08 ± 0.02	0.87 ± 0.01	4.04 ± 0.09
CEC	$cmol_c kg^{-1}$	6.12 ± 0.01	19.6 ± 0.87	41.2 ± 0.57	12.13 ± 0.55
OC	%	0.61 ± 0.01	38.9 ± 0.61	56.57 ± 0.84	38.6 ± 0.78
Total N	%	0.04 ± 0.00	1.48 ± 0.02	1.46 ± 0.04	1.14 ± 0.06
Exchangeable P	mg kg^{-1}	4.63 ± 0.20	0.31 ± 0.01	0.46 ± 0.03	0.42 ± 0.02
Extractable K	mg kg^{-1}	117 ± 1.31	1.67 ± 0.04	1.07 ± 0.03	0.91 ± 0.1
Yield	%	--	--	49.27 ± 0.99	--
Ash content	%	--	--	14.3 ± 0.41	--
C/N Ratio			13.93 ± 0.22	41.47 ± 1.24	13.73 ± 0.93
Textural class	--	Sandy clay loam	--	--	--

Data is an average of three replicates ± SD.

502 (Minolta, Osaka, Japan) was used to determine chlorophyll contents in the leaves (Wellburn, 1994). Relative water content (RWC) was measured by taking a fully expanded leaf from an individual replicate. The fresh weight of the leaf was recorded after being washed with distilled water. The leaf samples were placed in test tubes containing 10 mL distilled water for 4 h. Turgid weight was recorded after 4 h. Samples were oven dried for 72 h. The RWC was calculated using the formula established by Mayak et al. (2004).

$$RWC = (FW - DW)/\ (TW - DW)*100$$

Membrane Stability Index

For measuring the membrane stability index, a fully matured younger leaf was put into a test tube containing 10 mL of distilled water. Samples were heated in a water bath for 30 min at 40°C, and then electrical conductivity (EC_1) was recorded. The plant samples were heated again in the water bath at 100°C for 10 min, and then EC_2 was recorded. The membrane stability index (MSI) was calculated using the formula (Sairam et al., 2002).

$$MSI = [1 - (C_1/C_2)]*100$$

Plant Analysis

The plant samples were ground, sieved with 2 mm sieve after drying and used for further analysis. For plants nitrogen, each finely powdered sample was digested using concentrated sulphuric acid (H_2SO_4) and hydrogen peroxide (H_2O_2) using the Wolf (1982) method for digestion. Distilled water was used for making the volume accordingly after cooling, followed by filtration. Total nitrogen (TN) was estimated through the Kjeldahl apparatus. Total P was determined using a spectrophotometer (Milton Roy Company, United States), and total K was analysed using flame photometer (Jenway PFP-7, UK) (United States Salinity Laboratory Staff. 1954).

Post-Harvest Soil Analysis

At the end of the experiment, soil samples were collected and air-dried for 72 h. Soil pH, CEC and SOC were measured using United States Salinity Laboratory Staff. 1954. The results of these analysis are presented in **Figures 1–3**.

Microbial Biomass Carbon and Microbial Biomass Nitrogen Determination

A chloroform fumigation-extraction procedure was followed for microbial biomass carbon (MBC) and microbial biomass nitrogen (MBN) estimation in soil (Brookes et al., 1985). Two different crucibles containing 10 g of moist soil were placed in separate desiccators, one with 30 mL alcohol-free chloroform ($CHCl_3$) and another without $CHCl_3$, covered and placed at room temperature for 5 days (Anderson, 1993). After soil fumigation, a 50 mL K_2SO_4 (0.5 M) solution was added and shaken for 30 min at 200 rpm arbitral shaker speed to extract MBC and MBN from lysed microorganisms and then filtered. The MBC was measured on a spectrophotometer (ultraviolet-visible [UV-VIS]/1,201, Shimadzu) at 600 nm, while the Kjeldahl method was used for MBN determination. Both MBC and MBN were calculated using previously determined equations (Sparling and West, 1988).

$$MBC\ (mg) = Ec/k$$

where Ec was extracted, C was a result of fumigation and k was the biomass fraction, which was 0.35 for C and 0.45 for N (Ross and Täte, 1993).

Carbon Management Index

Based on the variations in total carbon in the soil environment and its lability (as determined by the oxidation of $KMnO_4$), the carbon management index (CMI) was calculated (Blair et al., 1995). The carbon pool index (CPI) was calculated according to changes in the TOC of the control and the treatments.

$$\text{CPI} = \frac{\text{TOC Treatment}}{\text{TOC Control}}$$

The lability of carbon (L) was calculated according to the fraction of carbon oxidised $KMnO_4$.

$$\text{L} = \frac{\text{Carbon oxidised by KMnO4}}{\text{Carbon remaining unoxidised by KMnO4}}$$

Based on the changes in the proportion of labile carbon, the lability index (LI) was calculated as follows:

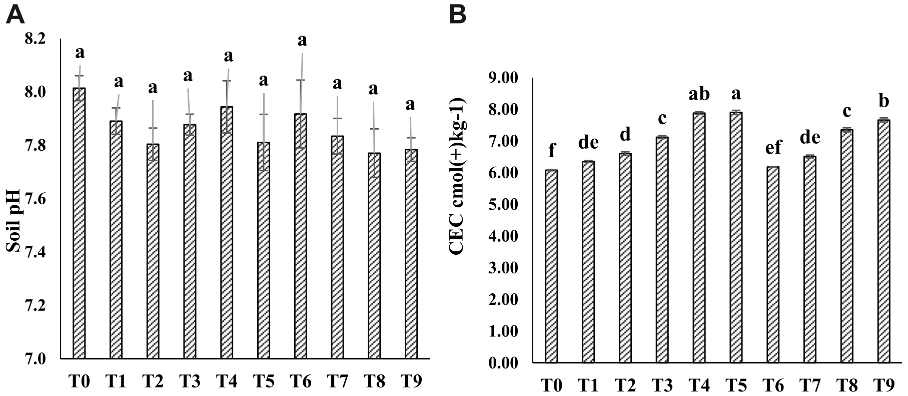

FIGURE 1 | Effect of CM, BC, and AM on soil pH **(A)** and CEC **(B)** after crop harvesting. Data is an average of three replicates and similar letter(s) in a graph shows non-significant results at (*p = 0.05*). Note: T_0 = Ck T1 = CM-0.5, T2 = CM-1, T3 = BC-3, T4 = BC-3+CM-0.5, T5 = BC-3+CM-1, T6 = AM-0.5, T7 = AM-1, T8 = BC-3+AM-0.5, and T9 = BC-3+AM-1.

$$LI = \frac{\text{L of treatment}}{\text{L of control}}$$

The CMI was calculated using two indices (CPI and LI) as follows:

$$CMI = CPI \times LI \times 100$$

A higher CPI (>1) indicated a greater accumulation of organic carbon, and a lower CPI (<1) reflected lower carbon accumulation. Similarly, a higher LI (>1) indicated a higher labile organic carbon content. In contrast, a lower LI (<1) indicated a lower organic carbon content. The CMI served as the expression of soil quality in increments of total carbon and the portion of labile carbon fractions compared to a control (CMI = 100); CMI>100 reflected an increased soil carbon content.

Statistical Analysis

All data were statistically analyzed using Statistix 8.1® (Analytical Software, Tallahassee, FL, United States) under completely randomized design (CRD) with three replications. The data were analyzed using one-way ANOVA and interpreted using Tukey multiple comparison test to compare mean values ($p < 0.05$) (Steel et al., 1997). The influence of several treatments on various physicochemical and biological parameters of the modified soil was investigated using correlation and principal component analysis (PCA) in Mini-Tab 18.1.0.

RESULTS

The Effect of CM, BC, and AM on Postharvest Soil Properties

Physicochemical parameters of CM, BC, and AM and soil used in this study are shown (**Table 2**). The highest soil pH (8.0 ± 0.05) was observed in Ck. The addition of BC with CM and AM fluctuate soil pH for a short time, but the decrease was not significant shown in **Figure 1A**. The lowest pH (7.8 ± 0.04) was observed under BC-3+AM-1 treatment, in which 0.2-unit decrease was noted over Ck. A significant increase in soil CEC were observed where BC-3+CM-0.5 and BC-3+CM-1 were used (**Figure 1B**) and the maximum 31% increase in soil CEC was observed under BC-3+CM-1 as compared to Ck.

Effect of CM, BC, and AM on Soil Quality Parameters

Data concerning MBC, SOC, CPI, LI, and CMI are shown in **Figures 2A–F**. The maximum 11% MBC increase was recorded where BC-3+CM-1 was used as compared to Ck (**Figure 2A**). The **Figure 2B** data revealed that the maximum 69% SOC increase was noticed under BC-3 while BC-3+CM-0.5 and BC-3+CM-1enhanced SOC up to 64% and 56% respectively.

The data (**Figure 2C**) showed the maximum increase in CPI was 69% with BC-3 as compared to control. The addition of CM-1+BC-3 improved the CPI up to 56%, and a similar result was observed following the addition of AM-1+BC-3. Significant decrease in labile carbon was observed with the addition of BC with other OAs ($p < 0.05$) and the maximum reduction in labile carbon 46% under BC-3+CM-1 (**Figure 2D**).

The maximum reduction was 76%, 84% and 77% in LI was recorded with BC-3+CM-1, BC-3+AM-0.5 and BC-3+AM-1 which was non-significant when compared to each other (**Figure 2E**). Similarly, the maximum increase was 48% in CMI observed where BC-3 was applied (**Figure 2F**).

Effect of CM, BC, and AM on Plant Growth, Cob Length and 1,000 Grains Weight

Table 3 data showed the CM, BC, and AM effect on SFW, SDW, LA, and PL. The application of BC-3+CM-1 increased plant height by 46% as compared to control. The maximum 106% SFW increase was noticed at BC-3+CM-1 application. It was observed that the application of BC with either COM or AM

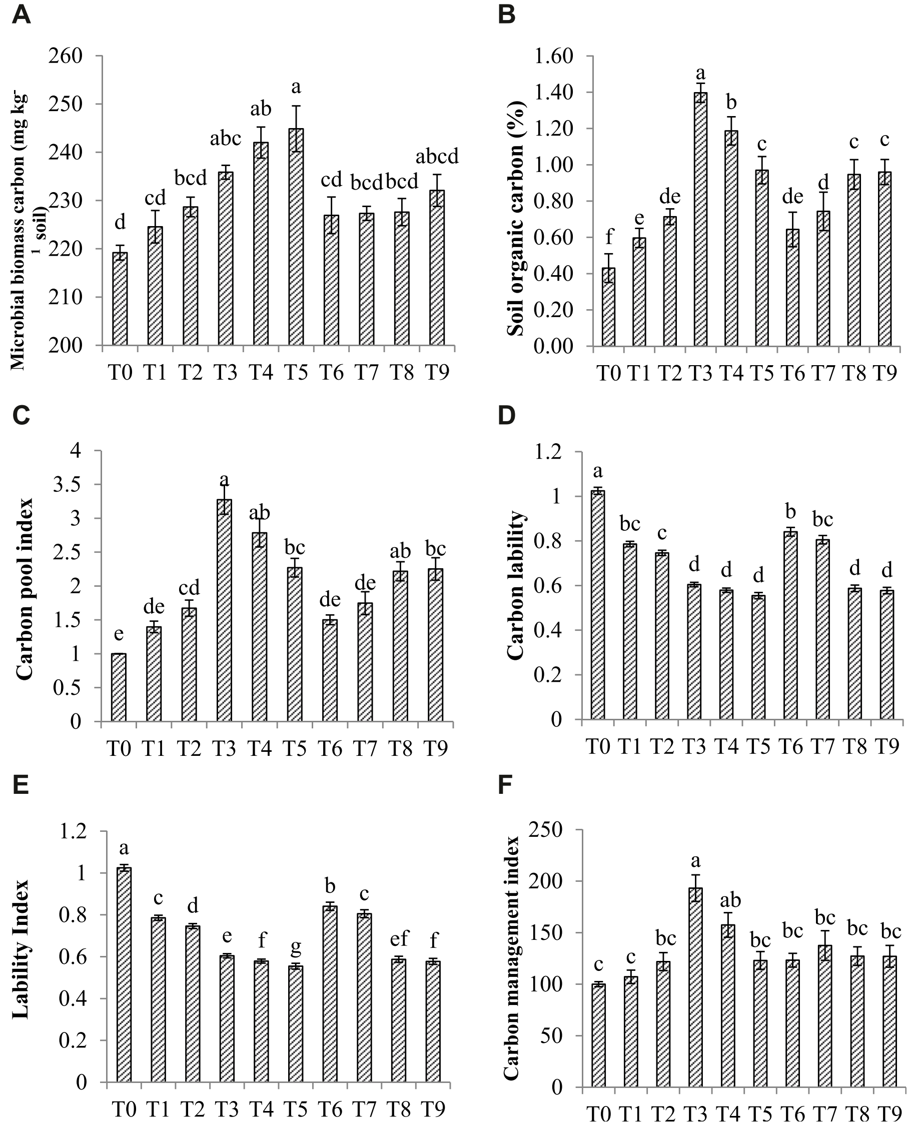

FIGURE 2 | Effect of CM, BC, and AM **(A)** Microbial biomass carbon **(B)** Soil organic carbon **(C)** Carbon pool index **(D)** Carbon lability **(E)** Lability Index **(F)** Carbon Management index. Data is an average of three replicates and similar letter(s) in a graph shows non-significant results at (*p = 0.05*). Note: T_0 = Ck T1 = CM-0.5, T2 = CM-1, T3 = BC-3, T4 = BC-3+CM-0.5, T5 = BC-3+CM-1, T6 = AM-0.5, T7 = AM-1, T8 = BC-3+AM-0.5, and T9 = BC-3+AM-1.

increased SDW as compared to sole application, and the maximum 114% SDW increase was recorded with the combined application of BC-3+CM-1. Similarly, the highest 83% LA increase was recorded under BC-3+CM-1 as compared to Ck.

Data regarding CL and 1000 GW showed maximum 71% increase in CL and 74% improvement in GW was recorded with the application of BC-3+CM-1 as compared to control.

Effect of CM, BC, and AM on the Physiological Parameters of Maize

Data regarding physiological parameters of maize showed BC-3+CM-1 application increased maximum 129% CC, 54% RWC, 128% PR, and 73% SC as compared to Ck (**Table 4**).

Data regarding electrolyte leakage (EL) (**Table 4**) indicated that the application of BC significantly decreased EL at all COM and AM levels. Applying BC-3+CM-1 decreased electrolyte leakage by 215%, compared to the Ck.

Effect of CM, BC, and AM on Maize Nutrient Contents

It was noticed that BC, CM, and AM alone or in combination significantly increased nutrient contents in maize shoot and grain (**Table 5**). The maximum increase in straw N content was 72% with BC-3+CM-1 application. Similarly, maximum 55% increase

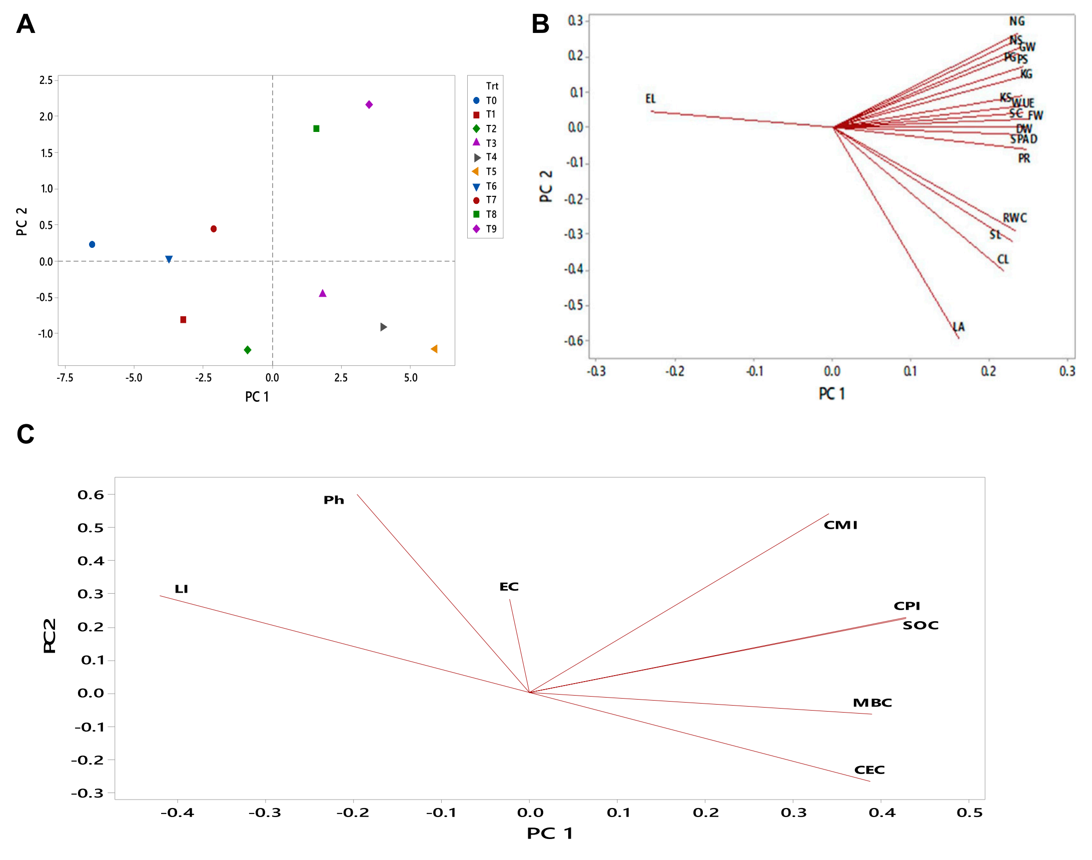

FIGURE 3 | Principal component analysis (PCA) performed on different maize growth, physiological and soil parameters. **(A)** represents PCA among treatments, **(B)** depicts the PCA among different growth and physiological parameters, and **(C)** showed PCA among soil parameters, The abbreviations are as FW, fresh weight; DW, dry weight; L, shoot length; CC, chlorophyll contents; EL, electrolyte leakage; LA, leaf area, RWC, relative water content; Ph, soil Ph; EC, electrical conductivity; CEC, cation exchange capacity; CL, cob length; GW, grain weight; PR, photosynthetic rate; WUE, water use efficiency; SC, stomatal conductance; GN, grain nitrogen; GP, grain phosphorus; GK, grain potassium; SN, straw nitrogen; SP, straw phosphorus; SK, straw potassium; SOC, soil organic carbon; CPI, Carbon pool index; LI, Lability Index; and CMI, carbon management index. Note: T0 = Ck T1 = CM-0.5, T2 = CM-1, T3 = BC-3, T4 = BC-3+CM-0.5, T5 = BC-3+CM-1, T6 = AM-0.5, T7 = AM-1, T8 = BC-3+AM-0.5, and T9 = BC-3+AM-1.

TABLE 2 | Effect of CM, BC, and AM on growth and yield parameters of maize.

Treatments	SL (cm)	SFW/pot (g)	SDW/Pot (g)	LA	CL (cm)	1000 GW(g)
T_0	84 ± 6.99f	124 ± 9.75f	44 ± 1.89f	198 ± 24.79f	3.6 ± 0.36e	299.0 ± 11.2e
T1	104 ± 4.29de	157 ± 15.61ef	52 ± 2.52e	246 ± 30.55def	4.5 ± 0.50cde	326.1 ± 23.4e
T_2	116 ± 9.17cd	186 ± 5.05de	73 ± 2.52d	299 ± 41.56dcd	4.9 ± 0.60bcd	345.6 ± 32.9cde
T_3	124 ± 3.95bc	209 ± 8.54bcd	88 ± 2.78c	326 ± 6.53abc	5.3 ± 0.29abc	394.9 ± 31.6abcd
T4	136 ± 3.08b	226 ± 16.78abc	96 ± 2.47b	353 ± 12.27ab	5.8 ± 0.29ab	397.9 ± 14.1abcd
T5	156 ± 5.19a	257 ± 10.33a	114 ± 2.86a	362 ± 11.82a	6.2 ± 0.29a	411.8 ± 10.0ab
T6	90 ± 3.97ef	155 ± 9.10ef	46 ± 3.50ef	213 ± 11.27ef	3.8 ± 0.21de	339.2 ± 35.0de
T7	100 ± 12.3def	170 ± 14.13e	53 ± 2.65e	269 ± 26.46cde	4.3 ± 0.29cde	351.3 ± 18.4bcde
T8	108 ± 2.93cd	203 ± 12.72cd	88 ± 2.52c	303 ± 12.71abcd	4.4 ± 0.53cde	405.3 ± 13.2abc
T9	116 ± 5.55cd	239 ± 7.53ab	96 ± 1.61b	323 ± 10.83abc	4.7 ± 0.29dec	418.9 ± 11.0a

SL, shoot length; SFW, shoot fresh weight; SDW, shoot dry weight; LA, leaf area; CL, cob length; 1000 GW, 1,000 grain weight. Data is an average of three replicates ± SD and similar letter(s) in a column shows non-significant results at (p = 0.05). Note: T_0 = Ck T1 = CM-0.5, T2 = CM-1, T3 = BC-3, T4 = BC-3+CM-0.5, T5 = BC-3+CM-1, T6 = AM-0.5, T7 = AM-1, T8 = BC-3+AM-0.5, and T9 = BC-3+AM-1.

in grain N was observed over control with BC-3+AM-1. The maximum 83% increase in straw P contents was noted with the sole BC-3 application, while 50% increase in grain P was observed with BC-3+CM-1 and BC-3+AM-1. The maximum 29% increase in straw K and 48% in grain K was observed with BC-3+CM-1 as compared to control.

TABLE 3 | Effect of CM, BC, and AM on physiological parameters of maize.

Treatments	RWC %	EL (%)	Photo. R (mmol m^{-2} S^{-1})	CC (mg g–1)	SC (mmol m^2S^{-1})	WUE (μmol $m^{-2}s^{-1}$)
T_0	49 ± 0.70d	60.83 ± 7.08a	10 ± 1.5f	22.35 ± 4.71c	146 ± 6.03e	2.33 ± 0.29d
T1	59 ± 8.53bcd	39.21 ± 1.21b	13 ± 1.0cdef	30.35 ± 1.89bc	159 ± 15.39de	3.17 ± 0.74bcd
T_2	65 ± 1.21abc	36.39 ± 1.62bc	14 ± 1.2bcde	34.15 ± 7.27bc	178 ± 6.43cde	3.77 ± 0.87bcd
T_3	66 ± 3.99abc	31.51 ± 2.18bc	17 ± 1.8abc	36.11 ± 2.03b	194 ± 10.21cd	4.83 ± 1.26abc
T4	70 ± 1.75ab	30.54 ± 2.14bc	19 ± 1.9ab	43.44 ± 3.26ab	238 ± 16.62ab	6.70 ± 0.36a
T5	76 ± 1.70a	19.30 ± 3.52d	22 ± 1.0a	51.19 ± 6.10a	253 ± 7.55a	6.83 ± 0.29a
T6	57 ± 4.32cd	40.80 ± 2.70b	10 ± 1.2ef	33.80 ± 3.39bc	158 ± 20.60de	2.83 ± 0.29cd
T7	60 ± 6.86bcd	36.79 ± 5.97bc	12 ± 1.2def	35.80 ± 1.57b	168 ± 14.1cde	3.77 ± 0.21bcd
T8	67 ± 2.05abc	34.42 ± 4.90bc	16 ± 2.0bcd	40.09 ± 3.05ab	199 ± 18.58bc	5.13 ± 0.91ab
T9	68 ± 4.56abc	26.85 ± 1.23cd	19 ± 2.5ab	41.73 ± 7.37ab	240 ± 12.66a	6.40 ± 0.87a

RWC, relative water contents; EL, electrolyte leakage; Photo. R, photosynthetic rate; CC, chlorophyll contents; SC, stomatal conductance; WUE, water use efficiency. Data is an average of three replicates ± SD and similar letter(s) in a column shows non-significant results at (p = 0.05). Note: T_0 = Ck T1 = CM-0.5, T2 = CM-1, T3 = BC-3, T4 = BC-3+CM-0.5, T5 = BC-3+CM-1, T6 = AM-0.5, T7 = AM-1, T8 = BC-3+AM-0.5, and T9 = BC-3+AM-1.

TABLE 4 | Effect of CM, BC, and AM on nutritional status of maize.

Treatments	Straw N	Straw P	Straw K	Grain N	Grain P	Grain K
T_0	0.21 ± 0.01e	0.59 ± 0.01e	2.35 ± 0.05f	0.45 ± 0.02f	1.11 ± 0.03f	3.7 ± 0.01f
T1	0.25 ± 0.01e	0.70 ± 0.01d	2.55 ± 0.05e	0.57 ± 0.02e	1.32 ± 0.03e	5.0 ± 0.05e
T_2	0.32 ± 0.04d	0.78 ± 0.01c	3.01 ± 0.02c	0.63 ± 0.01d	1.39 ± 0.03d	5.6 ± 0.04d
T_3	0.34 ± 0.01d	0.90 ± 0.02b	3.43 ± 0.05a	0.85 ± 0.01c	2.04 ± 0.02c	6.6 ± 0.02c
T4	0.44 ± 0.02c	0.99 ± 0.01a	3.44 ± 0.05a	0.90 ± 0.02b	2.16 ± 0.03b	6.8 ± 0.04b
T5	0.50 ± 0.01ab	1.02 ± 0.07a	3.52 ± 0.03a	0.92 ± 0.02b	2.21 ± 0.02ab	7.1 ± 0.11a
T6	0.25 ± 0.01e	0.65 ± 0.01de	2.76 ± 0.03d	0.61 ± 0.02de	1.30 ± 0.02e	5.0 ± 0.05e
T7	0.31 ± 0.02d	0.79 ± 0.02c	2.97 ± 0.03c	0.63 ± 0.03d	1.41 ± 0.02d	5.7 ± 0.07d
T8	0.45 ± 0.02ab	0.99 ± 0.01a	3.23 ± 0.14b	0.95 ± 0.02ab	2.19 ± 0.02ab	6.8 ± 0.05b
T9	0.52 ± 0.02a	1.01 ± 0.03a	3.52 ± 0.06a	0.99 ± 0.01a	2.23 ± 0.03a	7.1 ± 0.11a

N, nitrogen; P, phosphorus; K, potassium. Data is an average of three replicates ± SD and similar letter(s) in a column showed non-significant results at (p = 0.05). Note: T_0 = Ck T1 = CM-0.5, T2 = CM-1, T3 = BC-3, T4 = BC-3+CM-0.5, T5 = BC-3+CM-1, T6 = AM-0.5, T7 = AM-1, T8 = BC-3+AM-0.5, and T9 = BC-3+AM-1.

Correlations (Pearson) and Principal Component Analysis (PCA) Among Plant and Soil Parameters

Correlations between different plant and soil attributes was done and based on correlation analysis, it was observed that FW, SL had a positive correlation with CC, LA, RWC, PR, and WUE and whereas, significant negative correlation with EL and carbon liability index (LI).

Principal component analysis (PCA) was performed on different maize growth, physiological and soil parameters (**Figures 3A–C**). The PCA of maize growth and physiological parameters reveals that the first two principal components (PC1 and PC2) accounted for 88% of the overall variance of the treatments, with PC1 accounting for 87% of the variation. However, in this study, almost all characters in the first eigenvector had comparable effects on the total variance of the treatments, suggesting that the first component is virtually a measure of the whole characters. Further research revealed that the combined application of biochar with compost and animal manure (BC-3, BC-3+CM-0.5, BC-3+CM-1, BC-3+AM-0.5, and BC-3+AM-1) used were primarily concentrated in the positive end of PC 1 (**Figure 3A**). Simultaneously, the research indicated that the maize growth and physiological indices focused on the positive side of PC1 (**Figure 3B**).

The PCA plot (**Figure 3C**) revealed that two principal components accounted for 76.9% of the observed variability in the data set under examination (62.9% in PC1 and 14.6% in PC2). Treatments demonstrated a significant impact on soil variables: pH, EC, CEC, SOC, CPI, LI, and CMI. Similarly, soil parameters such as soil pH, electrical conductivity, and Lability Index were concentrated in the positive end of PC 2, and cation exchange capacity, soil organic carbon, Carbon pool index, and carbon management index were concentrated in the positive end of PC 1 (**Figure 3C**). The PCA findings confirmed that biochar and biochar co-composts had varying degrees of benefit in improving the deteriorated soil in this study.

DISCUSSION

The physical and chemical properties of soil are critical in determining its crop productivity. Post-harvest soil properties indicated that the addition of BC, COM, and AM influenced soil pH, CEC, and TOC. This study showed a non-significant change in soil pH when compared between treatments (**Figure 1**) and a significant decrease was observed where AM-1 was applied. Similar results were observed by Song et al. (2018), where a low biochar addition did not significantly influence the pH of the alkaline soil. Rehman et al. (2021) observed decrease in soil

TABLE 5 | Correlations (Pearson) between plant and soil Parameters.

	FW	DW	L	CC	EL	LA	RWC	Ph	EC	CEC	CL	GW	PR	WUE	SC	SOC	CPI	LI
FW	1.000																	
DW	0.972	1.000																
L	0.898	0.908	1.000															
CC	0.939	0.882	0.866	1.000														
EL	−0.922	−0.833	−0.835	−0.930	1.000													
LA	0.595	0.603	0.823	0.627	−0.642	1.000												
RWC	0.913	0.932	0.988	0.848	−0.816	0.810	1.000											
Ph	−0.589	−0.519	−0.377	−0.590	0.696	−0.105	−0.370	1.000										
EC	0.008	0.044	−0.090	−0.111	0.147	−0.267	−0.013	−0.140	1.000									
CEC	0.951	0.959	0.858	0.887	−0.800	0.536	0.876	−0.402	−0.104	1.000								
CL	0.840	0.849	0.982	0.801	−0.798	0.886	0.973	−0.291	−0.131	0.801	1.000							
GW	0.948	0.921	0.749	0.887	−0.872	0.444	0.771	−0.624	0.005	0.920	0.687	1.000						
PR	0.977	0.984	0.940	0.890	−0.872	0.644	0.949	−0.496	−0.064	0.958	0.890	0.899	1.000					
WUE	0.971	0.956	0.868	0.914	−0.847	0.552	0.887	−0.462	−0.073	0.991	0.818	0.931	0.959	1.000				
SC	0.971	0.954	0.875	0.914	−0.836	0.544	0.896	−0.447	−0.030	0.983	0.811	0.904	0.959	0.989	1.000			
SOC	0.760	0.768	0.691	0.644	−0.705	0.617	0.724	−0.290	−0.002	0.741	0.728	0.821	0.757	0.747	0.684	1.000		
CPI	0.761	0.768	0.692	0.646	−0.707	0.618	0.725	−0.294	−0.003	0.741	0.729	0.822	0.757	0.748	0.685	1.000	1.000	
LI	−0.944	−0.922	−0.821	−0.885	0.923	−0.603	−0.831	0.636	0.165	−0.899	−0.786	−0.960	−0.926	−0.913	−0.877	−0.838	−0.839	1.000
CMI	0.435	0.426	0.411	0.334	−0.447	0.515	0.445	−0.070	0.094	0.389	0.506	0.523	0.415	0.413	0.333	0.895	0.895	−0.540

The abbreviations are as FW, fresh weight; DW, dry weight; L, shoot length; CC, chlorophyll contents; EL, electrolyte leakage; LA, leaf area; RWC, relative water content; Ph, soil Ph; EC, electrical conductivity; CEC, cation exchange capacity; CL, cob length; GW, grain weight; PR, photosynthetic rate; WUE, water use efficiency; SC, stomatal conductance; SOC, soil organic carbon; CPI, carbon pool index; LI, lability index; and CMI, carbon management index.

pH because of AM and BC application, while increase in soil pH was observed with rice straw and cotton stick BC. Changes in soil pH in the rhizosphere modified the soil's chemical environment and boosted the nutrient supply to plants (Hinsinger, 2001). The decrease in soil pH may have been due to the presence of humic substances that were released because of organic carbon decomposition (Singh et al., 2012) or ammonium nitrification due to the applied amendments (Antolín et al., 2005). It is well documented that pyrolysis temperature significantly affects the pH and nutrient content of BC (Kaudal et al., 2015; Rehrah et al., 2016). Generally, BC is alkaline in nature and its alkalinity rises with temperature (Shakya and Agarwal, 2020). Biochar prepared at low temperatures contains more acidic functional groups such as carboxyl (-COOH), hydroxyl (-OH), and methyl (-CH_3) and these functional groups decrease as temperature increases and enhance the inorganic and basic oxide content, which increases the pH of biochar (Shaheen et al., 2019). Various studies have shown the pH of BC is between 5.9 and 12.3 (Ahmad et al., 2014; Kaudal et al., 2015; Rehrah et al., 2016). In recent years, several studies have been carried out to check the effect of BC on alkaline and sandy soils (Blackwell et al., 2010; Song et al., 2014; Abbas et al., 2020).

Many researchers have found that BC and other OAs could enhance soil quality and plant performance in degraded soil (Kammann, et al., 2016; Głąb et al., 2018; Abbas et al., 2020). Our results showed that BC, COM, and AM significantly increased SOM in soil (**Figure 3B**), which may have been due to the high carbon content of BC. The current study results showed BC, COM, and significantly increased MBC in soil (**Figure 3A**), which may have been due to the high carbon content of BC. The aromatic structure of BC provides resistance to decomposition, which increases SOM in soil (Wang et al., 2016). Several authors have observed that OAs increase SOC in soil (Wang et al., 2016; Schiedung et al., 2019; Wu et al., 2021). This may have been due to increased water and nutrient availability to soil microbes. The porous structure of BC provides shelter to the microbes against abiotic and biotic stresses. Various other properties, such as high porosity, large surface area, pore size and distribution play a key role in nutrient availability and retention, which can influence microbial activity (Zhao et al., 2022). Fleming et al. (2013) observed that chicken manure contains several nutrients that can increase soil nutrient content, enhance soil aggregate structure and stability, and increase soil microbial activity in degraded soil. Trupiano et al. (2017) observed that the sole or combined application of biochar and compost increased total organic carbon, more so than in the non-amended soils, which indicated that BC and/or compost applications to soils could improve C build-up and sequestration. Moreover, recent studies indicated that the use of OAs in soil improved organic carbon, which, in turn, improved nutrient availability (Hille and den Ouden, 2005). Brtnicky et al. (2019) observed an increase in MBC because of BC application to soil. This increase may have been due to the availability of nutrients and labile organic compounds. The labile part of SOCs plays a key role in maintaining soil fertility, while the recalcitrant fraction of SOM has a constructive influence on environmental quality (Brtnicky et al., 2019).

This study showed that the application of BC, COM, and AM positively affected maize growth and yield (**Table 3**) in less fertile soil. Biochar has a porous structure, a large surface area, and a high surface charge density, which are all beneficial for absorbing soil moisture, enhancing soil porosity, lowering bulk density, and producing an environment conducive to plant development (Hui, 2021). Biochar itself is a rich source of important macronutrients (particularly N, P, and K), and certain metal ions (e.g., Ca^{+2} and Mg^{+2}) that supply nutrients for plant development, their addition and complex interaction with soil releases plant nutrients from the exchange site in a soil solution, it also retains plant nutrients due to large surface area and greater C:N ratio (Biederman and Harpole, 2013; Lehmann et al., 2015). Previous studies showed that the addition of BC in soil increased biomass in lettuce and *Arabidopsis* (Viger et al., 2015), maize (Uzoma et al., 2011) and wheat (Solaiman et al., 2010). Al-Omran et al. (2019) observed that compost application in soil improved soil aeration, water retention capacity, reduced bulk density and improved soil structure, which ultimately increased plant growth. Similarly, Rawat et al. (2019) noted that the combined application of BC and compost enhanced fertiliser-use efficiency (FUE) through the controlled release of nutrients and reduced nutrient leaching (Rawat et al., 2019).

Biochar and other AOs (AM and COM) and had positive effects on crop growth and yield because they retain nutrients via adsorption, binding, and co-precipitation (Lashari et al., 2015; Luo et al., 2017; Al-Omran et al., 2019; Rahman et al., 2020). Similarly, the combined use of compost and BC had positive effects on crop growth and yield (Lashari et al., 2015; Luo et al., 2017; Al-Omran et al., 2019; Rahman et al., 2020). In this study, the significant increases in maize growth may have been due to an improvement in soil structure, soil aeration, an increase in CEC, improved nutrient regulation and an overall improvement in soil physiochemical properties. These changes in soil supplied additional nutrients, improved water retention capacity, and reduced nutrient leaching, resulting in improved plant growth, yields and sustainable soil productivity (Agegnehu et al., 2015; Noor et al., 2017; Cao et al., 2018; Radin et al., 2018).

The data presented (**Table 4**) indicate that the sole or combined application of BC, CM, and AM significantly ($p < 0.05$) increased chlorophyll content, WUE, RWC and EL, compared to the control. Another experiment showed that the combined application of wheat straw BC, biogas slurry and compost decreased RWC and EL by 23% and 39%, respectively, while increasing TR, CC, SC, and WUE by 77%, 90%, 49%, and 97%, respectively, compared to the control (Rahman et al., 2020). Agegnehu et al. (2015) observed a significant improvement in chlorophyll content because of BC-compost with chemical fertilizer application in soil. Water use efficiency is an important indicator of crop productivity and water use in arid and semiarid areas (Batool et al., 2015). Biochar addition has been shown to improve water retention in soil, resulting in soil structure improvement by reducing bulk density and protecting crops against drought (Abel et al., 2013; Sun and Lu, 2014). Solaiman et al. (2010) observed an increase in stomatal conductance because of BC addition to soil. Similarly, a 3%–7% increase in moisture content, which resulted in an increased rate of photosynthesis because of BC (2%) in soil, was observed by Ippolito et al. (2012).

Carbon is the main component of biochar that contains oxygen (O_2), hydrogen (H), N, K, P, Mg, and other micronutrients that, when directly available for plant uptake, can improve crop yield in most crops (Seleiman et al., 2020). Biochar's large surface area and porous structure help to retain applied nutrients and reduce nutrient leaching of N and P, releasing them when needed (Abbas et al., 2020). The application of BC and compost increased the P contents in maize straw due to lower adsorption on the exchange site and increased root growth. Recent studies indicated that BC amended increased the K contents, resulting in higher plant growth (Steiner et al., 2007). Overall, this study indicated that the use of biochar with other OAs not only increased the FUE through the slow release of nutrients but also acted as a soil conditioner that improved soil properties. The application of biochar with other amendments can thus provide a sustainable approach that will support the restoration of soil fertility and crop productivity and, hence, contribute to a circular economy.

The PCA results related to maize growth and physiological parameters reveal that the PC1 and PC2 accounted for 88% of the overall variance of the treatments, with PC1 accounting for 87% of the variation (**Figure 3B**). Agegnehu et al. (2015) perform correlation and PCA analysis on different growth parameter under biochar and compost application and observed plant height, root biomass, chlorophyll content, and specific leaf weight were positively significantly correlated with maize shoot biomass (r = 0.96, 0.98, 0.99, and 0.92, respectively). The PCA found that the first two principal components (PC1 and PC2) accounted for 91% of the overall variance of the treatments, with PC1 accounting for 84% of the variation. Similarly, Tsai and Chang, (2020) used different biochar rates (0%), 0.5%, 1.0%, and 2.0% (w/w) along with 5% (w/w) poultry-livestock manure compost. PCA was used to study the essential components in the big data set, and several factors such as NO_3-N, TIN, soil pH, EC, DOC, TC, TN, C:N ratio, P and K were added as analysis variables in the PCA at the beginning (day 3) and end (day 371) of the incubation study. The PCA results revealed that the PC1 and PC2 explained 34.5% and 21.3% of the total variance in slightly acidic Oxisols (SAO), 30.2% and 23.4% of the total variance in mildly alkaline Inceptisols (MAI), and 38.2% and 22.6% of the total variance in slightly acid Inceptisols (SAI) soils at day 3, accounting for 55.8%, 53.6%, and 60.8% of the total variance, respectively. At day 371, PC1 and PC2 explained and accounted for 68.5%, 66.9%, and 61.9% of the total change in SAO, MAI, and SAI soils, respectively. Ye et al. (2023) applied PCA analysis on soil and tea indexes measured after the application of various dosages of sheep manure from 2018 to 2022, with PC1 contributing the most, ranging from 84.7% to 97.6%. Further investigation found that the low dose (6 t/hm^2–12 t/hm^2) were generally concentrated in the negative end of PC1, however the high dosage (15 t/hm^2-18 t/hm^2) was more concentrated in the positive end of PC1.

CONCLUSION

This study highlighted the potential of organic amendments, especially BC, CM, and AM, as a sustainable option for increasing agricultural yields, improving soil qualities, and contributing to a circular economy. Combining 3% BC with 1% COM, and 1% AM proved to be a successful strategy, with significant improvements in plant height, shoot weight, and grain weight, carbon pool index, and microbial biomass carbon. These findings not only indicate high yield, but also highlight the ability of organic additions to restore even the most nutrient-depleted soils. These OAs provide a ray of hope for sustainable agriculture by tackling the issues of soil degradation caused by intensive farming and climate change. By accepting these organic solutions, we begin a path toward a robust and resilient food system that will protect our future. Additional studies and field experiments are needed to confirm these findings and investigate the long-term impacts of organic additions on soil health and at variable rates and with site and/or crop-specific fertiliser doses under field conditions.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/Supplementary material, further inquiries can be directed to the corresponding authors.

AUTHOR CONTRIBUTIONS

Conceptualization, AM, MN, and MS; methodology, AA and KS; software, AA and LA; validation, MA, AM, and MN; formal analysis, AA and LA; investigation, MN, AA, and NA; resources, AM and MS; data curation, AA, KS, and NA; writing–original draft preparation, AA and AM; writing–review and editing, MN, MS, AM, and MA; funding acquisition, MS, AM, and MN. All authors contributed to the article and approved the submitted version.

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CONFLICT OF INTEREST

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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REFERENCES

Abbas, A., Naveed, M., Azeem, M., Yaseen, M., Ullah, R., Alamri, S., et al. (2020). Efficiency of Wheat Straw Biochar in Combination With Compost and Biogas Slurry for Enhancing Nutritional Status and Productivity of Soil and Plant. *Plants* 9 (11), 1516. doi:10.3390/plants9111516

Abel, S., Peters, A., Trinks, S., Schonsky, H., Facklam, M., and Wessolek, G. (2013). Impact of Biochar and Hydrochar Addition on Water Retention and Water Repellency of Sandy Soil. *Geoderma* 202–203, 183–191. doi:10.1016/j.geoderma.2013.03.003

Abrar, M. M., Xu, M., Shah, S. A. A., Aslam, M. W., Aziz, T., Mustafa, A., et al. (2020). Variations in the Profile Distribution and Protection Mechanisms of Organic Carbon Under Long-Term Fertilization in a Chinese Mollisol. *Sci. Total Environ.* 723, 138181. doi:10.1016/j.scitotenv.2020.138181

Adnan, M., Fahad, S., Zamin, M., Shah, S., Mian, I. A., Danish, S., et al. (2020). Coupling Phosphate-Solubilizing Bacteria With Phosphorus Supplements Improve Maize Phosphorus Acquisition and Growth Under Lime Induced Salinity Stress. *Plants* 9 (7), 900. doi:10.3390/plants9070900

Agegnehu, G., Bass, A. M., Nelson, P. N., Muirhead, B., Wright, G., and Bird, M. I. (2015). Biochar and Biochar-Compost as Soil Amendments: Effects on Peanut Yield, Soil Properties and Greenhouse Gas Emissions in Tropical North Queensland, Australia. *Agric. Ecosyst. Environ.* 213, 72–85. doi:10.1016/j.agee.2015.07.027

Ahmad, M., Rajapaksha, A. U., Lim, J. E., Zhang, M., Bolan, N., Mohan, D., et al. (2014). Biochar as a Sorbent for Contaminant Management in Soil and Water: A Review. *Chemosphere* 99, 19–33. doi:10.1016/j.chemosphere.2013.10.071

Al-Omran, A., Ibrahim, A., and Alharbi, A. (2019). Evaluating the Impact of Combined Application of Biochar and Compost on Hydro-Physical Properties of Loamy Sand Soil. *Commun. Soil Sci. Plant Analysis* 50 (19), 2442–2456. doi:10.1080/00103624.2019.1667371

Amoakwah, E., Arthur, E., Frimpong, K. A., Parikh, S. J., and Islam, R. (2020). Soil Organic Carbon Storage and Quality Are Impacted by Corn Cob Biochar Application on a Tropical Sandy Loam. *J. Soils Sediments* 20 (4), 1960–1969. doi:10.1007/s11368-019-02547-5

Anderson, I. (1993). *Tropical Soil Biology and Fertility: A Handbook of Methods*. CAB International. doi:10.1097/00010694-199404000-00012

Antolín, M. C., Pascual, I., García, C., Polo, A., and Sánchez-Díaz, M. (2005). Growth, Yield and Solute Content of Barley in Soils Treated With Sewage Sludge Under Semiarid Mediterranean Conditions. *Field Crops Res.* 94 (2–3), 224–237. doi:10.1016/j.fcr.2005.01.009

Arya, S., Williams, A., Reina, S. V., Knapp, C. W., Kreft, J. U., Hobman, J. L., et al. (2021). Towards a General Model for Predicting Minimal Metal Concentrations Co-Selecting for Antibiotic Resistance Plasmids. *Environ. Pollut.* 275, 116602. doi:10.1016/j.envpol.2021.116602

Azeem, M., Sun, D., Crowley, D., Hayat, R., Hussain, Q., Ali, A., et al. (2020). Crop Types Have Stronger Effects on Soil Microbial Communities and Functionalities Than Biochar or Fertilizer During Two Cycles of Legume-Cereal Rotations of Dry Land. *Sci. Total Environ.* 715, 136958. doi:10.1016/j.scitotenv.2020.136958

Aziz, H., Wang, X., Murtaza, G., Ashar, A., Hussain, S., Abid, M., et al. (2021). Evaluation of Compost and Biochar to Mitigate Chlorpyrifos Pollution in Soil and Their Effect on Soil Enzyme Dynamics. *Sustainability* 13 (17), 9695. doi:10.3390/su13179695

Batool, A., Taj, S., Rashid, A., Khalid, A., Qadeer, S., Saleem, A. R., et al. (2015). Potential of Soil Amendments (Biochar and Gypsum) in Increasing Water Use Efficiency of Abelmoschus Esculentus L. Moench. *Front. Plant Sci.* 6, 733. doi:10.3389/fpls.2015.00733

Ben-Asher, J., Tsuyuki, I., Bravdo, B.-A., and Sagih, M. (2006). Irrigation of Grapevines With Saline Water. *Agric. Water Manag.* 83 (1–2), 13–21. doi:10.1016/j.agwat.2006.01.002

Biederman, L. A., and Harpole, W. S. (2013). Biochar and Its Effects on Plant Productivity and Nutrient Cycling: A Meta-Analysis. *GCB Bioenergy* 5 (2), 202–214. doi:10.1111/gcbb.12037

Blackwell, P., Krull, E., Butler, G., Herbert, A., and Solaiman, Z. (2010). Effect of Banded Biochar on Dryland Wheat Production and Fertiliser Use in South-Western Australia: An Agronomic and Economic Perspective. *Soil Res.* 48 (7), 531. doi:10.1071/SR10014

Blair, G., Lefroy, R., and Lisle, L. (1995). Soil Carbon Fractions Based on Their Degree of Oxidation, and the Development of a Carbon Management Index for Agricultural Systems. *Aust. J. Agric. Res.* 46 (7), 1459. doi:10.1071/AR9951459

Bouyoucos, G. J. (1962). Hydrometer Method Improved for Making Particle Size Analyses of Soils ^{1}. *Agron. J.* 54 (5), 464–465. doi:10.2134/agronj1962.00021962005400050028x

Bremner, J. M. (2016). *Total Nitrogen*, 1149–1178. doi:10.2134/agronmonogr9.2.c32

Brookes, P. C., Landman, A., Pruden, G., and Jenkinson, D. S. (1985). Chloroform Fumigation and the Release of Soil Nitrogen: A Rapid Direct Extraction Method to Measure Microbial Biomass Nitrogen in Soil. *Soil Biol. Biochem.* 17 (6), 837–842. doi:10.1016/0038-0717(85)90144-0

Brtnicky, M., Dokulilova, T., Holatko, J., Pecina, V., Kintl, A., Latal, O., et al. (2019). Long-Term Effects of Biochar-Based Organic Amendments on Soil Microbial Parameters. *Agronomy* 9 (11), 747. doi:10.3390/agronomy9110747

Cao, L., Yu, I. K. M., Tsang, D. C. W., Zhang, S., Ok, Y. S., Kwon, E. E., et al. (2018). Phosphoric Acid-Activated Wood Biochar for Catalytic Conversion of Starch-Rich Food Waste Into Glucose and 5-Hydroxymethylfurfural. *Bioresour. Technol.* 267, 242–248. doi:10.1016/j.biortech.2018.07.048

Estefan, G., Sommer, R., and Ryan, J. (2013). Methods of Soil, Plant, and Water Analysis. *A Man. West Asia North Afr. region* 3 (2).

Fleming, M., Tai, Y., Zhuang, P., and McBride, M. B. (2013). Extractability and Bioavailability of Pb and as in Historically Contaminated Orchard Soil: Effects of Compost Amendments. *Environ. Pollut.* 177, 90–97. doi:10.1016/j.envpol.2013.02.013

Gaskin, J. W., Speir, R. A., Harris, K., Das, K. C., Lee, R. D., Morris, L. A., et al. (2010). Effect of Peanut Hull and Pine Chip Biochar on Soil Nutrients, Corn Nutrient Status, and Yield. *Agron. J.* 102 (2), 623–633. doi:10.2134/agronj2009.0083

Głąb, T., Żabiński, A., Sadowska, U., Gondek, K., Kopeć, M., Mierzwa–Hersztek, M., et al. (2018). Effects of Co-Composted Maize, Sewage Sludge, and Biochar Mixtures on Hydrological and Physical Qualities of Sandy Soil. *Geoderma* 315, 27–35. doi:10.1016/j.geoderma.2017.11.034

Gregory, A. S., Ritz, K., McGrath, S. P., Quinton, J. N., Goulding, K. W. T., Jones, R. J. A., et al. (2015). A Review of the Impacts of Degradation Threats on Soil Properties in the UK. *Soil Use Manag.* 31, 1–15. doi:10.1111/sum.12212

Haider, F. U., Liqun, C., Coulter, J. A., Cheema, S. A., Wu, J., Zhang, R., et al. (2021). Cadmium Toxicity in Plants: Impacts and Remediation Strategies. *Ecotoxicol. Environ. Saf.* 211, 111887. doi:10.1016/j.ecoenv.2020.111887

Hille, M., and den Ouden, J. (2005). Charcoal and Activated Carbon as Adsorbate of Phytotoxic Compounds - A Comparative Study. *Oikos* 108 (1), 202–207. doi:10.1111/j.0030-1299.2005.13482.x

Hinsinger, P. (2001). Bioavailability of Soil Inorganic P in the Rhizosphere as Affected by Root-Induced Chemical Changes: A Review. *Plant Soil* 237 (2), 173–195. doi:10.1023/A:1013351617532

Hui, D. (2021). Effects of Biochar Application on Soil Properties, Plant Biomass Production, and Soil Greenhouse Gas Emissions: A Mini-Review. *Agric. Sci.* 12 (03), 213–236. doi:10.4236/as.2021.123014

Ippolito, J. A., Novak, J. M., Busscher, W. J., Ahmedna, M., Rehrah, D., and Watts, D. W. (2012). Switchgrass Biochar Affects Two Aridisols. *J. Environ. Qual.* 41 (4), 1123–1130. doi:10.2134/jeq2011.0100

Kamara, A., Sorie Kamara, H., and Saimah Kamara, M. (2015). Effect of Rice Straw Biochar on Soil Quality and the Early Growth and Biomass Yield of Two Rice Varieties. *Agric. Sci.* 06 (08), 798–806. doi:10.4236/as.2015.68077

Kammann, C., Glaser, B., and Schmidt, H. P. (2016). "Combining Biochar and Organic Amendments," in *Biochar in European Soils and Agriculture* (Routledge), 158–186.

Kaudal, B. B., Chen, D., Madhavan, D. B., Downie, A., and Weatherley, A. (2015). Pyrolysis of Urban Waste Streams: Their Potential Use as Horticultural Media. *J. Anal. Appl. Pyrolysis* 112, 105–112. doi:10.1016/j.jaap.2015.02.011

Kocsis, T., Ringer, M., and Biró, B. (2022). Characteristics and Applications of Biochar in Soil–Plant Systems: A Short Review of Benefits and Potential Drawbacks. *Appl. Sci.* 12 (8), 4051. doi:10.3390/app12084051

Lal, R. (2015). Restoring Soil Quality to Mitigate Soil Degradation. *Sustainability* 7 (5), 5875–5895. doi:10.3390/su7055875

Lashari, M. S., Ye, Y., Ji, H., Li, L., Kibue, G. W., Lu, H., et al. (2015). Biochar-Manure Compost in Conjunction With Pyroligneous Solution Alleviated Salt Stress and Improved Leaf Bioactivity of Maize in a Saline Soil From Central China: A 2-Year Field Experiment. *J. Sci. Food Agric.* 95 (6), 1321–1327. doi:10.1002/jsfa.6825

Lehmann, J., Kuzyakov, Y., Pan, G., and Ok, Y. S. (2015). Biochars and the Plant-Soil Interface. *Plant Soil* 395 (1–2), 1–5. doi:10.1007/s11104-015-2658-3

Lillenberg, M., Yurchenko, S., Kipper, K., Herodes, K., Pihl, V., Lõhmus, R., et al. (2010). Presence of Fluoroquinolones and Sulfonamides in Urban Sewage Sludge and Their Degradation as a Result of Composting. *Int. J. Environ. Sci. Technol.* 7 (2), 307–312. doi:10.1007/BF03326140

Luo, X., Liu, G., Xia, Y., Chen, L., Jiang, Z., Zheng, H., et al. (2017). Use of Biochar-Compost to Improve Properties and Productivity of the Degraded Coastal Soil in the Yellow River Delta, China. *J. Soils Sediments* 17 (3), 780–789. doi:10.1007/s11368-016-1361-1

Mayak, S., Tirosh, T., and Glick, B. R. (2004). Plant Growth-Promoting Bacteria Confer Resistance in Tomato Plants to Salt Stress. *Plant Physiology Biochem.* 42 (6), 565–572. doi:10.1016/j.plaphy.2004.05.009

Naeem, M. A., Khalid, M., Aon, M., Abbas, G., Amjad, M., Murtaza, B., et al. (2018). Combined Application of Biochar With Compost and Fertilizer Improves Soil Properties and Grain Yield of Maize. *J. Plant Nutr.* 41 (1), 112–122. doi:10.1080/01904167.2017.1381734

Naveed, M., Sajid, H., Mustafa, A., Niamat, B., Ahmad, Z., Yaseen, M., et al. (2020). Alleviation of Salinity-Induced Oxidative Stress, Improvement in Growth, Physiology and Mineral Nutrition of Canola (Brassica Napus L.) Through Calcium-Fortified Composted Animal Manure. *Sustainability* 12 (3), 846. doi:10.3390/su12030846

Naveed, M., Tanvir, B., Xiukang, W., Brtnicky, M., Ditta, A., Kucerik, J., et al. (2021). Co-Composted Biochar Enhances Growth, Physiological, and Phytostabilization Efficiency of Brassica Napus and Reduces Associated Health Risks Under Chromium Stress. *Front. Plant Sci.* 12, 775785. doi:10.3389/fpls.2021.775785

Nguyen, B. T., Trinh, N. N., Le, C. M. T., Nguyen, T. T., van Tran, T., Thai, B. V., et al. (2018). The Interactive Effects of Biochar and Cow Manure on Rice Growth and Selected Properties of Salt-Affected Soil. *Archives Agron. Soil Sci.* 64 (12), 1744–1758. doi:10.1080/03650340.2018.1455186

Niamat, B., Naveed, M., Ahmad, Z., Yaseen, M., Ditta, A., Mustafa, A., et al. (2019). Calcium-Enriched Animal Manure Alleviates the Adverse Effects of Salt Stress on Growth, Physiology and Nutrients Homeostasis of Zea Mays L. *Plants* 8 (11), 480. doi:10.3390/plants8110480

Noor, N. M., Othman, R., Mubarak, N. M., and Abdullah, E. C. (2017). Agricultural Biomass-Derived Magnetic Adsorbents: Preparation and Application for Heavy Metals Removal. *J. Taiwan Inst. Chem. Eng.* 78, 168–177. doi:10.1016/j.jtice.2017.05.023

Novotny, E. H., Maia, C. M. B. F., Carvalho, M. T. M., and Madari, B. E. (2015). Biochar: Pyrogenic Carbon for Agricultural Use- A Critical Review. *Rev. Bras. Ciência Do Solo* 39 (2), 321–344. doi:10.1590/01000683rbcs20140818

Obalum, S. E., Chibuike, G. U., Peth, S., and Ouyang, Y. (2017). Soil Organic Matter as Sole Indicator of Soil Degradation. *Environ. Monit. Assess.* 189 (4), 176. doi:10.1007/s10661-017-5881-y

Olsen, R., Cole, C. V., Watanabe, F. S., and Dean, L. A. (1954). *Estimation of Available Phosphorus in Soils by Extraction With NaHCO3*. Washington, DC: U.S. Department of Agriculture, 939.

Pandit, N. R., Schmidt, H. P., Mulder, J., Hale, S. E., Husson, O., and Cornelissen, G. (2020). Nutrient Effect of Various Composting Methods With and Without Biochar on Soil Fertility and Maize Growth. *Archives Agron. Soil Sci.* 66 (2), 250–265. doi:10.1080/03650340.2019.1610168

Peng, S., Zheng, H., Herrero-Fresno, A., Olsen, J. E., Dalsgaard, A., and Ding, Z. (2021). Co-Occurrence of Antimicrobial and Metal Resistance Genes in Pig Feces and Agricultural Fields Fertilized With Slurry. *Sci. Total Environ.* 792, 148259. doi:10.1016/j.scitotenv.2021.148259

Radin, R., Abu Bakar, R., Ishak, C. F., Ahmad, S. H., and Tsong, L. C. (2018). Biochar-Compost Mixture as Amendment for Improvement of Polybag-

Growing Media and Oil Palm Seedlings at Main Nursery Stage. *Int. J. Recycl. Org. Waste Agric.* 7 (1), 11–23. doi:10.1007/s40093-017-0185-3

Rahman, G. K. M. M., Rahman, M. M., Alam, M. S., Kamal, M. Z., Mashuk, H. A., Datta, R., et al. (2020). "Biochar and Organic Amendments for Sustainable Soil Carbon and Soil Health," in *Carbon and Nitrogen Cycling in Soil* (Singapore: Springer), 45–85. doi:10.1007/978-981-13-7264-3_3

Rawat, J., Saxena, J., and Sanwal, P. (2019). "Biochar: A Sustainable Approach for Improving Plant Growth and Soil Properties," in *Biochar - an Imperative Amendment for Soil and the Environment* (IntechOpen). doi:10.5772/intechopen.82151

Rehman, I., Riaz, M., Ali, S., Arif, M. S., Ali, S., Alyemeni, M. N., et al. (2021). Evaluating the Effects of Biochar With Farmyard Manure Under Optimal Mineral Fertilizing on Tomato Growth, Soil Organic C and Biochemical Quality in a Low Fertility Soil. *Sustainability* 13 (5), 2652. doi:10.3390/su13052652

Rehman, M. Z., Rizwan, M., Ali, S., Fatima, N., Yousaf, B., Naeem, A., et al. (2016). Contrasting Effects of Biochar, Compost and Farm Manure on Alleviation of Nickel Toxicity in Maize (Zea Mays L.) in Relation to Plant Growth, Photosynthesis and Metal Uptake. *Ecotoxicol. Environ. Saf.* 133, 218–225. doi:10.1016/j.ecoenv.2016.07.023

Rehrah, D., Bansode, R. R., Hassan, O., and Ahmedna, M. (2016). Physico-Chemical Characterization of Biochars From Solid Municipal Waste for Use in Soil Amendment. *J. Anal. Appl. Pyrolysis* 118, 42–53. doi:10.1016/j.jaap.2015.12.022

Rivelli, A. R., and Libutti, A. (2022). Effect of Biochar and Inorganic or Organic Fertilizer Co-Application on Soil Properties, Plant Growth and Nutrient Content in Swiss Chard. *Agronomy* 12 (9), 2089. doi:10.3390/agronomy12092089

Ross, D. J., and Täte, K. R. (1993). Microbial C and N, and Respiratory Activity, in Litter and Soil of a Southern Beech (Nothofagus) Forest: Distribution and Properties. *Soil Biol. Biochem.* 25 (4), 477–483. doi:10.1016/0038-0717(93)90073-K

Sairam, R. K., Rao, K. V., and Srivastava, G. C. (2002). Differential Response of Wheat Genotypes to Long Term Salinity Stress in Relation to Oxidative Stress, Antioxidant Activity and Osmolyte Concentration. *Plant Sci.* 163 (5), 1037–1046. doi:10.1016/S0168-9452(02)00278-9

Sánchez, M. E., Lindao, E., Margaleff, D., Martínez, O., and Morán, A. (2009). Pyrolysis of Agricultural Residues From Rape and Sunflowers: Production and Characterization of Bio-Fuels and Biochar Soil Management. *J. Anal. Appl. Pyrolysis* 85 (1–2), 142–144. doi:10.1016/j.jaap.2008.11.001

Sánchez-García, M., Sánchez-Monedero, M. A., Roig, A., López-Cano, I., Moreno, B., Benitez, E., et al. (2016). Compost vs Biochar Amendment: A Two-Year Field Study Evaluating Soil C Build-Up and N Dynamics in an Organically Managed Olive Crop. *Plant Soil* 408 (1–2), 1–14. doi:10.1007/s11104-016-2794-4

Schiedung, M., Tregurtha, C. S., Beare, M. H., Thomas, S. M., and Don, A. (2019). Deep Soil Flipping Increases Carbon Stocks of New Zealand Grasslands. *Glob. Change Biol.* 25 (7), 2296–2309. doi:10.1111/gcb.14588

Schofield, R. K., and Taylor, A. W. (1955). The Measurement of Soil pH. *Soil Sci. Soc. Am. J.* 19 (2), 164–167. doi:10.2136/sssaj1955.03615995001900020013x

Seleiman, M. F., Almutairi, K. F., Alotaibi, M., Shami, A., Alhammad, B. A., and Battaglia, M. L. (2020). Nano-Fertilization as an Emerging Fertilization Technique: Why Can Modern Agriculture Benefit From Its Use? *Plants* 10 (1), 2. doi:10.3390/plants10010002

Shaheen, S. M., Niazi, N. K., Hassan, N. E. E., Bibi, I., Wang, H., Tsang, D. C. W., et al. (2019). Wood-Based Biochar for the Removal of Potentially Toxic Elements in Water and Wastewater: A Critical Review. *Int. Mater. Rev.* 64 (4), 216–247. doi:10.1080/09506608.2018.1473096

Shakoor, A., Ashraf, F., Shakoor, S., Mustafa, A., Rehman, A., and Altaf, M. M. (2020). Biogeochemical Transformation of Greenhouse Gas Emissions From Terrestrial to Atmospheric Environment and Potential Feedback to Climate Forcing. *Environ. Sci. Pollut. Res.* 27 (31), 38513–38536. doi:10.1007/s11356-020-10151-1

Shakya, A., and Agarwal, T. (2020). "Potential of Biochar for the Remediation of Heavy Metal Contaminated Soil," in *Biochar Applications in Agriculture and Environment Management* (Springer International Publishing), 77–98. doi:10.1007/978-3-030-40997-5_4

Singh, R., Singh, P., Singh, H., and Raghubanshi, A. S. (2019). Impact of Sole and Combined Application of Biochar, Organic and Chemical Fertilizers on Wheat Crop Yield and Water Productivity in a Dry Tropical Agro-Ecosystem. *Biochar* 1 (2), 229–235. doi:10.1007/s42773-019-00013-6

Singh, R. P., Singh, P., Ibrahim, M. H., and Hashim, R. (2012). Land Application of Sewage Sludge: Physicochemical and Microbial Response. *Rev. Environ. Contam. Toxicol.* 214, 41–61. doi:10.1007/978-1-4614-0668-6_3

Solaiman, Z. M., Blackwell, P., Abbott, L. K., and Storer, P. (2010). Direct and Residual Effect of Biochar Application on Mycorrhizal Root Colonisation, Growth and Nutrition of Wheat. *Soil Res.* 48 (7), 546. doi:10.1071/SR10002

Song, D., Tang, J., Xi, X., Zhang, S., Liang, G., Zhou, W., et al. (2018). Responses of Soil Nutrients and Microbial Activities to Additions of Maize Straw Biochar and Chemical Fertilization in a Calcareous Soil. *Eur. J. Soil Biol.* 84, 1–10. doi:10.1016/j.ejsobi.2017.11.003

Song, Y., Zhang, X., Ma, B., Chang, S. X., and Gong, J. (2014). Biochar Addition Affected the Dynamics of Ammonia Oxidizers and Nitrification in Microcosms of a Coastal Alkaline Soil. *Biol. Fertil. Soils* 50 (2), 321–332. doi:10.1007/s00374-013-0857-8

Sparling, G. P., and West, A. W. (1988). A Direct Extraction Method to Estimate Soil Microbial C: Calibration *In Situ* Using Microbial Respiration and 14C Labelled Cells. *Soil Biol. Biochem.* 20 (3), 337–343. doi:10.1016/0038-0717(88)90014-4

Srivastava, P., Singh, R., Bhadouria, R., Tripathi, S., and Raghubanshi, A. S. (2020). Temporal Change in Soil Physicochemical, Microbial, Aggregate and Available C Characteristic in Dry Tropical Ecosystem. *Catena* 190, 104553. doi:10.1016/j.catena.2020.104553

Steel, R. G. D., Torrie, J. H., and Dickey, D. A. (1997). *Principles and Procedures of Statistics: A Biometrical Approach.*

Steiner, C., Teixeira, W. G., Lehmann, J., Nehls, T., de Macêdo, J. L. V., Blum, W. E. H., et al. (2007). Long Term Effects of Manure, Charcoal and Mineral Fertilization on Crop Production and Fertility on a Highly Weathered Central Amazonian Upland Soil. *Plant Soil* 291 (1–2), 275–290. doi:10.1007/s11104-007-9193-9

Sun, F., and Lu, S. (2014). Biochars Improve Aggregate Stability, Water Retention, and Pore-Space Properties of Clayey Soil. *J. Plant Nutr. Soil Sci.* 177 (1), 26–33. doi:10.1002/jpln.201200639

Sutton, N. B., Grotenhuis, T., and Rijnaarts, H. H. M. (2014). Impact of Organic Carbon and Nutrients Mobilized During Chemical Oxidation on Subsequent Bioremediation of a Diesel-Contaminated Soil. *Chemosphere* 97, 64–70. doi:10.1016/j.chemosphere.2013.11.005

Trupiano, D., Cocozza, C., Baronti, S., Amendola, C., Vaccari, F. P., Lustrato, G., et al. (2017). The Effects of Biochar and Its Combination With Compost on Lettuce (*Lactuca Sativa* L.) Growth, Soil Properties, and Soil Microbial Activity and Abundance. *Int. J. Agron.* 2017, 1–12. doi:10.1155/2017/3158207

Tsai, C. C., and Chang, Y. F. (2020). Effects of Biochar to Excessive Compost-Fertilized Soils on the Nutrient Status. *Agronomy* 10 (5), 683. doi:10.3390/agronomy10050683

Urra, J., Alkorta, I., and Garbisu, C. (2019). Potential Benefits and Risks for Soil Health Derived From the Use of Organic Amendments in Agriculture. *Agronomy* 9 (9), 542. doi:10.3390/agronomy9090542

Uzoma, K. C., Inoue, M., Andry, H., Fujimaki, H., Zahoor, A., and Nishihara, E. (2011). Effect of Cow Manure Biochar on Maize Productivity Under Sandy Soil Condition. *Soil Use Manag.* 27 (2), 205–212. doi:10.1111/j.1475-2743.2011.00340.x

Viger, M., Hancock, R. D., Miglietta, F., and Taylor, G. (2015). More Plant Growth But Less Plant Defence? First Global Gene Expression Data for Plants Grown in Soil Amended With Biochar. *GCB Bioenergy* 7 (4), 658–672. doi:10.1111/gcbb.12182

Walkley, A. (1947). A Critical Examination of a Rapid Method for Determining Organic Carbon in Soils – Effect of Variations in Digestion Conditions and of Inorganic Soil Constituents. *Soil Sci.* 63 (4), 251–264. doi:10.1097/00010694-194704000-00001

Wang, J., Xiong, Z., and Kuzyakov, Y. (2016). Biochar Stability in Soil: Meta-Analysis of Decomposition and Priming Effects. *GCB Bioenergy* 8 (3), 512–523. doi:10.1111/gcbb.12266

Wellburn, A. R. (1994). The Spectral Determination of Chlorophylls a and B, as Well as Total Carotenoids, Using Various Solvents With Spectrophotometers of Different Resolution. *J. Plant Physiology* 144 (3), 307–313. doi:10.1016/S0176-1617(11)81192-2

Wolf, B. (1982). A Comprehensive System of Leaf Analyses and Its Use for Diagnosing Crop Nutrient Status. *Commun. Soil Sci. Plant Analysis* 13 (12), 1035–1059. doi:10.1080/00103628209367332

Wu, L., Zhang, S., Ma, R., Chen, M., Wei, W., and Ding, X. (2021). Carbon Sequestration Under Different Organic Amendments in Saline-Alkaline Soils. *CATENA* 196, 104882. doi:10.1016/j.catena.2020.104882

Ye, J., Wang, Y., Kang, J., Chen, Y., Hong, L., Li, M., et al. (2023). Effects of Long-Term Use of Organic Fertilizer With Different Dosages on Soil Improvement, Nitrogen Transformation, Tea Yield and Quality in Acidified Tea Plantations. *Plants* 12 (1), 122. doi:10.3390/plants12010122

Zhang, P., Li, Y., Cao, Y., and Han, L. (2019). Characteristics of Tetracycline Adsorption by Cow Manure Biochar Prepared at Different Pyrolysis Temperatures. *Bioresour. Technol.* 285, 121348. doi:10.1016/j.biortech.2019.121348

Zhao, Y., Wang, X., Yao, G., Lin, Z., Xu, L., Jiang, Y., et al. (2022). Advances in the Effects of Biochar on Microbial Ecological Function in Soil and Crop Quality. *Sustainability* 14 (16), 10411. doi:10.3390/su141610411

Zhou, M., Zhu, B., Wang, S., Zhu, X., Vereecken, H., and Brüggemann, N. (2017). Stimulation of N2O Emission by Manure Application to Agricultural Soils May Largely Offset Carbon Benefits: A Global Meta-Analysis. *Glob. Change Biol.* 23, 4068–4083. doi:10.1111/gcb.13648

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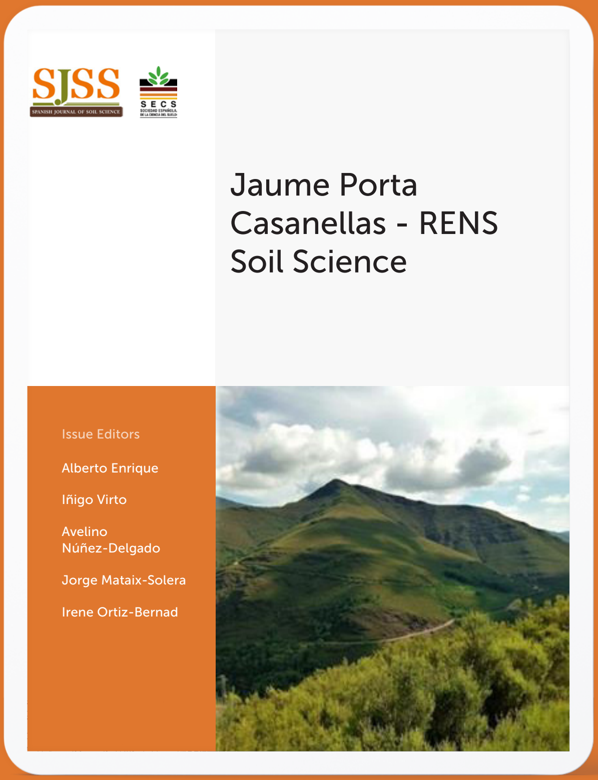

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