



Land use change of transhumant drove roads leads to soil quality degradation: a case study in Central Spain

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ABSTRACT

Grassland soils, beyond their role as biodiversity reservoirs, actively contribute to the provision of numerous ecosystem services. In the Iberian Peninsula, drove roads, the traditional routes used for seasonal livestock movements in search of the most productive pastures, play a key role in the preservation of semi-natural grasslands and in the protection of the upper soil horizon. However, the absence of transhumant pastoralism has led to the degradation of these natural corridors, with unexplored consequences in terms of soil quality and functioning. To investigate the relationship between the conservation state of these livestock routes and soil characteristics, which had not been researched to date, we selected thirty sites within the Madrid drove road network in central Spain. We established three categories: (i) reference well-preserved drove roads and two degraded states: (ii) overgrown abandoned and (iii) eroded drove roads and collected soil samples at each state. We determined soil physicochemical variables like the percentage of C, total N and P, available K, pH and electrical conductivity. We also measured soil enzyme activity using fluorometric methods and assessed litter decomposition through the Tea Bag Index experiment. Our findings demonstrated that the preservation state of drove roads had a significant impact on soil fertility. The mean carbon percentage was up to ten times lower in eroded drove roads compared to reference sites, while nitrogen content was four times higher in reference sites, and phosphorus and potassium content were twice as high in reference drove roads compared to eroded sites. Litter decomposition rate was also half in eroded soils compared to reference sites. Although the nutrient content and litter decomposition of overgrown abandoned drove roads did not differ from reference sites, enzyme activity was significantly higher in reference soils compared to both degraded states. Arylsulfatase activity was six times higher in reference plots, which also showed twice as much phosphatase activity and up to four times as much β -xylosidase activity. Our results confirmed our hypothesis that drove roads suffering from erosion have the most degraded soils. Additionally, we found that both the excessive accumulation of biomass due to grazing abandonment and the loss of vegetation cover through erosion contribute to the loss of soil functionality within the Madrid drove road network. The lack of use and subsequent degradation of drove roads compromise both the stability of the soil ecosystem and the availability of nutrients for plants. Given the vast surface area covered by this network of corridors, the reintroduction of transhumant and local extensive grazing can be an important tool to improve soil characteristics.

1. Introduction

Soils are one of the most important biodiversity reservoirs in terrestrial ecosystems, harbouring a diverse array of life forms including arthropods, annelids, small mammals, fungi, bacteria, and nematodes

(Bardgett and Van Der Putten, 2014). Soil biodiversity plays a critical role in ecosystem functioning by regulating nutrient cycling, supporting soil food webs, and also through the generation of plant-soil feedbacks (Delgado-Baquerizo et al., 2020). Maintaining the biodiversity of these organisms is crucial for the health of ecosystems and the provision of

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ecosystem services across global biomes, including grasslands, which cover nearly 40 % of the terrestrial surface (Bardgett et al., 2021). Grassland soils have a higher abundance and taxonomic diversity of microarthropods compared to cultivated lands, making them important habitats for the conservation of soil biodiversity, particularly in agricultural landscapes (Menta et al., 2011). Previous research has demonstrated that the reduction of soil biodiversity and the simplification of community composition can compromise essential ecosystem functions, such as decomposition and nutrient cycling, in grassland soils (De Vries et al., 2013; Wagg et al., 2014).

Grassland soils are also important carbon reservoirs, storing approximately 30 % of the world's carbon stock (Chang et al., 2018; Conant et al., 2017) in the form of root biomass and soil organic carbon (Bai and Cotrufo, 2022). Grasslands composed of a diverse community of late-successional perennial grass species have particularly high carbon sequestration rates, promoting the role of soil as a carbon sink (Yang et al., 2019). However, the critical role of grasslands in carbon sequestration is currently under threat due to widespread degradation of these ecosystems (Bardgett et al., 2021). Preserving grassland soils is essential for maintaining fungal and bacterial communities, which are vital for the formation of mineral-associated organic matter that facilitates long-term carbon sequestration (Bai and Cotrufo, 2022). Changes in land use and soil physicochemical properties, can alter the composition of these microbial communities (Dong et al., 2023), further endangering the role of grasslands in carbon sequestration.

The conservation and proper functioning of grasslands depend on the essential role played by herbivores. The interaction between grazing herbivores, grassland soils and plants, promotes efficient biogeochemical cycling of carbon, nitrogen, phosphorus and potassium (Dubeux et al., 2007), which is crucial for grassland productivity and fodder quality (Sollenberger et al., 2019). Globally, grasslands are mainly used as a forage source for livestock grazing, and the impact of grazing on soil conservation and multifunctionality has been widely examined. For example, studies have shown that grazing abandonment affects soil microbial community function and reduces carbon sequestration and nutrient availability (Aldezabal et al., 2015; Oggioni et al., 2020; Peco et al., 2017), while moderate extensive grazing improves biomass production, quality fodder, and soil properties (Bogunovic et al., 2022).

In the Iberian Peninsula, traditional management of domestic livestock, including extensive grazing, rotational grazing and transhumance, has historically contributed to the conservation of semi-natural grasslands of high ecological value (Gómez-Sal, 2001; San Miguel et al., 2016). Transhumance, in particular, involves seasonal livestock movements between upland and lowland areas in search of the most productive pastures (Ruiz and Ruiz, 1986). Transhumant livestock movements typically follow traditional routes called drove roads (also known as drovers' roads, stock driveways, livestock routes or transhumance routes), which play an important role connecting isolated grasslands and contribute to landscape spatial heterogeneity (Azcárate et al., 2013a).

Although drove roads exist in many countries (Biber, 2010; Mas-tronardi et al., 2021), Spain is a unique case, where the drove road network is over 125,000 km long, covering approximately 0.8 % of the national territory, and after centuries of use, it was legally protected for livestock movement (Drove Roads Act from 1995). These corridors consist of linear strips of natural grassland vegetation and a main path, along with traditional structures like shepherds' huts or watering troughs. There are different categories, according to their historical importance and width: Royal Drove Roads (*Cañadas Reales*) are the broadest ones, with a width of 75 m, followed by *cordeles* (approximately 37 m wide), *veredas* (about 20 m) and *coladas* (<20 m).

Drove roads facilitate long-distance seed dispersal and contribute to plant migration (Manzano and Malo, 2006). These livestock routes also act as biodiversity reservoirs, hosting a greater number and more functionally diverse plant and arthropod communities, including ants (Azcárate et al., 2013b) and wild bees (Hevia et al., 2016, 2013),

compared to intensive agricultural landscapes. In addition, transhumant use of drove roads contributes to the protection of the upper soil horizon, and promotes soil fertility (Acín-Carrera et al., 2013). However, the progressive abandonment and decline in the movements of transhumant flocks has led to the degradation of these natural corridors (Oteros-Rozas et al., 2012), with unexplored consequences in terms of soil quality and functioning.

This study aims to evaluate how different conservation states of drove roads affect soil quality and fertility (measured through the percentage of carbon, total nitrogen and phosphorus, available potassium, pH, electrical conductivity), as well as soil functioning (assessed using litter decomposition rate and enzyme activity) within the Madrid drove road network in central Spain. To our knowledge, the relationship between the conservation of these livestock routes and the edaphic ecosystem, which is the basis that supports the diversity of these semi-natural grasslands, has not been researched to date. The Community of Madrid has an extensive network of drove roads (4168 km and 13,093 ha, occupying up to 1.63 % of the regional territory), offering a unique opportunity to study how soil properties are affected by the abandonment and degradation of these natural corridors. We identified three different conservation categories for the drove roads in our study: (i) reference, (ii) overgrown abandoned and (iii) eroded (see Supplementary Fig. S1).

Our objective was to explore how the conservation state of the drove roads influences soil fertility, litter decomposition rate, and enzyme activity, and to evaluate the extent to which the loss of traditional management practices, such as transhumance, impacts the soil ecosystem. We hypothesized (a) that eroded drove roads, characterized by loss of vegetation cover and suffering from motorized traffic, will have the most degraded soils and differ the most from the other two categories (reference and overgrown abandoned), i.e., we expect these soils to have lower nutrient content, reduced litter decomposition rates, and very low levels of enzyme activity, while (b) overgrown abandoned drove roads will show an intermediate level of soil disturbance, with soil fertility levels, decomposition rates and enzyme activity more similar to those of reference sites.

2. Materials and methods

2.1. Study area

The study was conducted within the drove road network of the Community of Madrid, Spain (Fig. 1a). The altitude ranges from 550 to 780 m above sea level, and the whole study area lies on Miocene arkosic sediments (Azcárate and Hevia, 2023). The soils in this area are predominantly inceptisols and alfisols. The climate is continental Mediterranean, with pronounced summer droughts and significant seasonal thermal contrasts. The mean annual temperature ranges between 13.5 and 15 °C, while the mean annual precipitation varies between 400 and 550 mm and is typically concentrated between September and May (i.e., autumn and spring). The vegetation inside the Iberian drove roads is dominated by acidophilic Mediterranean grasslands, mainly composed of annual species, and is included in the European Union priority habitat pseudo-steppe with grass and annuals (*Thero-Brachypodietea*). However, the drove road environment is highly heterogeneous, and these grasslands coexist with woody shrub vegetation islands dominated by *Retama sphaerocarpa* and sparse trees, mainly *Quercus ilex* (the canopy cover is usually below 10 %).

Transhumant movements have been the prevailing activity at these sites for centuries, but now only a few of them are still used by transhumant shepherds, leading to the overall degradation of the drove road network and the deterioration of these grassland habitats. However, some of the Madrid drove roads have been well conserved due to local livestock grazing, while others have been invaded by other land uses like intensive crop fields. In many cases, motor vehicle traffic has resulted in a significant loss of vegetation cover on the drove roads, and increased

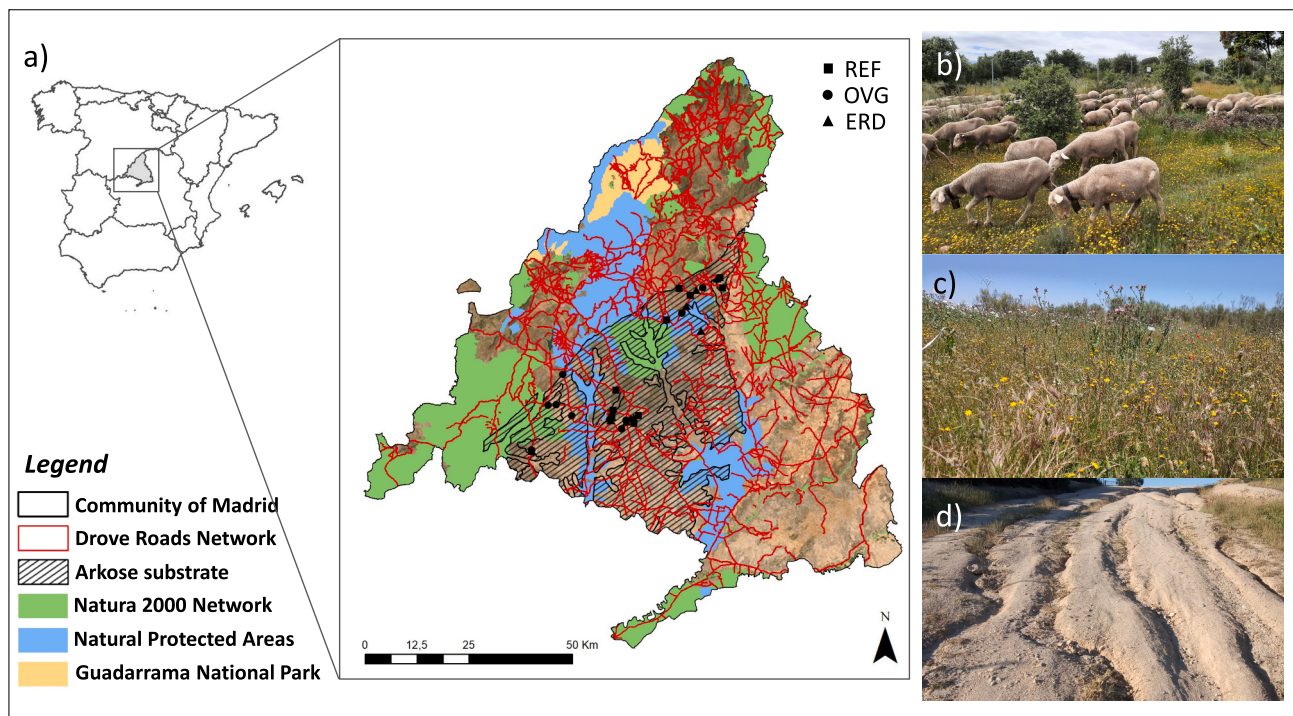


Fig. 1. a) Map of the study area, showing how the Madrid drove road network spreads across the territory and connects protected areas. Sampling sites are depicted using different symbology: reference (square), overgrown abandoned (circle) and eroded plots (triangle); (b), (c) and (d) pictures of some of the selected drove roads, from top to bottom: reference, overgrown and eroded.

soil erosion. In broad terms, the best-preserved area is located in the northwest of the region, which is the most mountainous zone, while in the lowlands of the central and southern regions, the conservation state of the drove roads is much worse (Azcarate and Hevia, 2023). Annual pastures of *Thero-Brachypodietea* have been replaced by poorer pastures dominated by perennials such as *Dactylis glomerata* or generalist annuals like *Bromus hordeaceus*, *B. tectorum*, or *B. matritensis*, due to the loss of grazing. In eroded sections, vegetation is very scarce, and only highly resilient species adapted to trampling, such as *Spergularia purpurea*, *Crassula tillaea*, or *Plantago coronopus*, manage to survive. The Madrid drove road network, which is uniformly distributed across the region, connects Natural Protected Areas and Natura 2000 sites, increasing its importance as a potential ecological corridor (Fig. 1a).

2.2. Sampling design

A total of thirty sampling sites were selected from the 4168 km of the Madrid drove road network after a preliminary analysis through field visits and aerial photographs. The sampling sites were classified into three different conservation states: (1) reference plots, characterized by moderate to low grazing activity, which preserves a heterogeneous and complex plant community and protects the soil upper horizon; (2) overgrown abandoned plots, with no grazing activity, excessive biomass accumulation, and loss of habitat structural complexity; and (3) eroded plots, characterized by the loss of plant cover and the subsequent erosion and degradation of the topsoil layer, mainly due to motorized vehicle traffic (Fig. 1b, c and d). One sampling plot of 10 m × 15 m was established in each location, resulting in ten plots of each conservation state and thirty plots in total.

2.3. Field sampling and data collection

In July 2020, topsoil samples were collected from the thirty sites. Three sub-samples were taken from each site (collected randomly at depths of 0–10 cm), mixed, and then air-dried and sieved through a 2-

mm diameter mesh. Each sample was tested for various soil physico-chemical properties and fertility using standard soil analysis methods. These variables included the percentage of carbon (% C), total nitrogen (N) and total phosphorus (P), determined through digestion and UV spectrophotometry, available potassium (K), determined through flame photometry, and pH and electrical conductivity (EC), measured by electrometric methods.

Soil enzyme activities were also assessed following the methodology described by Bell et al. (2013). We analysed enzymes associated with the degradation of different C-rich (BG = β -glucosidase, CB = β -cellobiohydrolase, XYL = β -xylosidase and AG = α -glucosidase), N-rich (NAG = N-acetyl- β -glucosaminidase, LAP = leucine aminopeptidase), S-rich (AS = arylsulfatase) and P-rich (PHOS = phosphatase) compounds. Slurries were a combination of 1 g of dry soil and 30 mL of 50 mM sodium acetate buffer (pH 5.5). The suspensions were incubated for 1.5 h at 35 °C with different synthetic fluorescent indicators (4-methylumbelliferone and 7-amino-4-methylcoumarin) associated with the above-mentioned enzymes. Fluorescence was quantified using a Synergy HTX microplate reader with an excitation wavelength of 365 nm and an emission wavelength of 450 nm.

To evaluate plant litter decomposition caused by soil microbial communities, we used the Tea Bag Index developed by Keuskamp et al. (2013). The Tea Bag Index allows for the determination of two parameters: the decomposition rate (k) and the organic matter stabilisation factor (S), using commercially available tea bags (green and rooibos) as standardized surrogates. Green tea is used as a proxy for labile litter and is expected to decompose faster, while rooibos tea represents a proxy for recalcitrant litter and is expected to decompose slower. In October 2020, two bags of each tea type were buried side by side at a depth of approximately 6 cm at each of the thirty sampling sites, totaling 120 bags. After three months of incubation, the bags were retrieved, oven-dried at 70 °C for 48 h, and weighed, and then used to calculate k and S values according to Keuskamp et al. (2013).

2.4. Data analyses

To test for differences in the responses of soil fertility variables, soil enzyme activity and litter decomposition between drove roads conservation states (three levels) we used Generalized Linear Models. Since the dependent variables were of very different types, three types of error distributions were used: Gaussian, inverse Gaussian, and Gamma distributions. For some variables that presented zero values, a log ($y + 1$) transformation was performed prior to the Generalized Linear Models. Principal Component Analysis (PCA) was conducted to explore the similarities between reference, overgrown abandoned and eroded soils, as well as to identify which measured variables had the greatest impact on soil quality in the different drove road types. Variables were log-transformed to meet PCA assumptions. R (Version 4.2.2; R Core Team, 2022) was used in the statistical analyses.

3. Results

3.1. Litter decomposition and soil fertility

Mean values of soil fertility variables and litter decomposition rate for the different conservation states of drove roads are shown in Table 1. Plots suffering from erosion were significantly different from reference plots for several of the measured parameters (p -value < 0.05), while overgrown abandoned plots did not differ from the reference state (Fig. 2). Mean C % in reference drove roads was more than ten times higher than in the eroded plots, but very similar to that in overgrown abandoned plots (Table 1). Total N content (mg/g of soil) was up to four times higher in reference than in eroded drove roads, while total P and available K in eroded plots were about half as high as in reference plots (Table 1). The nutrient content of overgrown abandoned drove roads

Table 1

Mean response and standard deviation of the soil variables measured for the different drove road conservation states.

Soil variables	Drove road conservation states		
	Reference (n = 9)	Overgrown (n = 10)	Eroded (n = 10)
% C	1.76 ± 1.22	1.35 ± 0.65	0.15 ± 0.25
Total N (mg/g soil)	1.80 ± 0.97	1.22 ± 0.47	0.43 ± 0.24
Total P (mg/g soil)	0.36 ± 0.13	0.36 ± 0.13	0.21 ± 0.13
Available K (mg/g soil)	0.11 ± 0.04	0.12 ± 0.07	0.05 ± 0.02
pH	6.75 ± 0.16	7.11 ± 0.45	6.83 ± 0.82
EC (μS/cm)	169.51 ± 72.44	185.74 ± 60.48	133.65 ± 80.75
S (stabilisation factor)	0.194 ± 0.081	0.220 ± 0.069	0.215 ± 0.068
k (litter decomposition rate)	0.016 ± 0.006	0.015 ± 0.004	0.008 ± 0.002
AG (α-glucosidase) (nmol activity/g dry soil/h)	13.41 ± 10.16	3.36 ± 4.25	5.31 ± 5.06
AS (arylsulfatase) (nmol activity/g dry soil/h)	5.02 ± 4.07	0.81 ± 1.44	1.51 ± 1.58
BG (β-glucosidase) (nmol activity/g dry soil/h)	60.17 ± 41.18	34.88 ± 14.10	11.69 ± 8.27
CB (β-cellobiohydrolase) (nmol activity/g dry soil/h)	11.71 ± 9.98	3.08 ± 3.14	1.53 ± 1.76
LAP (leucine aminopeptidase) (nmol activity/g dry soil/h)	4.71 ± 4.07	0.30 ± 0.84	0.23 ± 0.41
NAG (N-acetyl-β-glucosaminidase) (nmol activity/g dry soil/h)	23.93 ± 16.95	9.85 ± 4.29	4.51 ± 4.04
PHOS (phosphatase) (nmol activity/g dry soil/h)	99.55 ± 47.39	52.79 ± 18.49	44.47 ± 24.11
XYL (β-xylosidase) (nmol activity/g dry soil/h)	7.20 ± 6.04	1.77 ± 2.43	1.38 ± 1.61

was very similar to the reference state.

The mean values of soil acidity (pH) and electrical conductivity (EC) did not show significant differences between drove road types (Fig. 2). In contrast, mean decomposition rate (k) of plant litter was found to be significantly lower (p -value < 0.05) in eroded plots compared to the reference state, while overgrown drove roads did not differ (Fig. 2, Table 1). On the other hand, the stabilisation factor (S) did not show significant differences between plot types. One of the reference locations had to be discarded as the bags were damaged and could not be retrieved. The statistics of the Generalized Linear Models performed can be found at Supplementary Table S1.

3.2. Soil enzyme activities

Most of the extracellular enzymes determined showed significant differences between drove road conservation types (Fig. 3), with the exception of α-glucosidase activity, which did not differ between plot types (p -value > 0.05). Arylsulfatase activity was found to be six times higher in reference drove roads compared to overgrown plots (Table 1), and this difference was statistically significant (p -value < 0.05) between these two states, but not between reference and eroded plots. Two C-related enzymes, β-glucosidase and β-cellobiohydrolase, showed significantly lower activity in eroded plots (p -value < 0.05 , Table 1), with no significant differences between reference and overgrown abandoned soils (Fig. 3).

Regarding the N cycle, both leucine aminopeptidase and N-acetyl-β-glucosaminidase activities were affected by drove road conservation state, with significantly lower values (p -value < 0.05 , Fig. 3) in overgrown and eroded plots when compared to reference ones (Table 1). We also found that phosphatase and β-xylosidase activities were significantly lower (p -value < 0.05) in the eroded and overgrown abandoned states, compared to reference drove roads, which showed twice as much phosphatase activity and up to four times as much β-xylosidase activity (Fig. 3, Table 1). The Generalized Linear Model results indicated consistent responses of enzyme activity, with higher activity in reference plots but also higher variability (Supplementary Table S2).

3.3. Drove road conservation effects on soil functioning

The results of the Principal Components Analysis revealed that the first two components accounted for 61 % of the total variance (44.2 % and 16.8 % respectively) (Fig. 4), with component 1 being mainly influenced by four enzyme activities, while component 2 was primarily determined by available potassium, litter decomposition rate (k), and two enzyme activities (Table 2). The Principal Components Analysis also demonstrated a clear separation of clusters along the first axis, with reference plots being the most scattered, and eroded plots highly grouped and separated from both reference and overgrown abandoned samples, as we hypothesized. Positively high correlations with the first axis were observed for most of the enzymes determined and for some fertility measures like the percentage of carbon or total nitrogen, highlighting the links between these variables and reference plots (Table 2). Furthermore, intermediate levels of positive association with the first axis were observed for decomposition rate (k), electrical conductivity (EC), and available potassium (Table 1).

4. Discussion

Grassland management, closely linked to grazing regimes, mowing frequency and fertilization, is essential for their sustainability (Allan et al., 2014). Our study has shown that the conservation state of transhumant drove roads has a significant impact on the quality and functioning of semi-natural grassland soils, thus making these livestock routes a conservation priority. Additionally, given the extensive distribution of Spanish drove roads across the territory and their potential role as ecological corridors, their widespread degradation is a highly

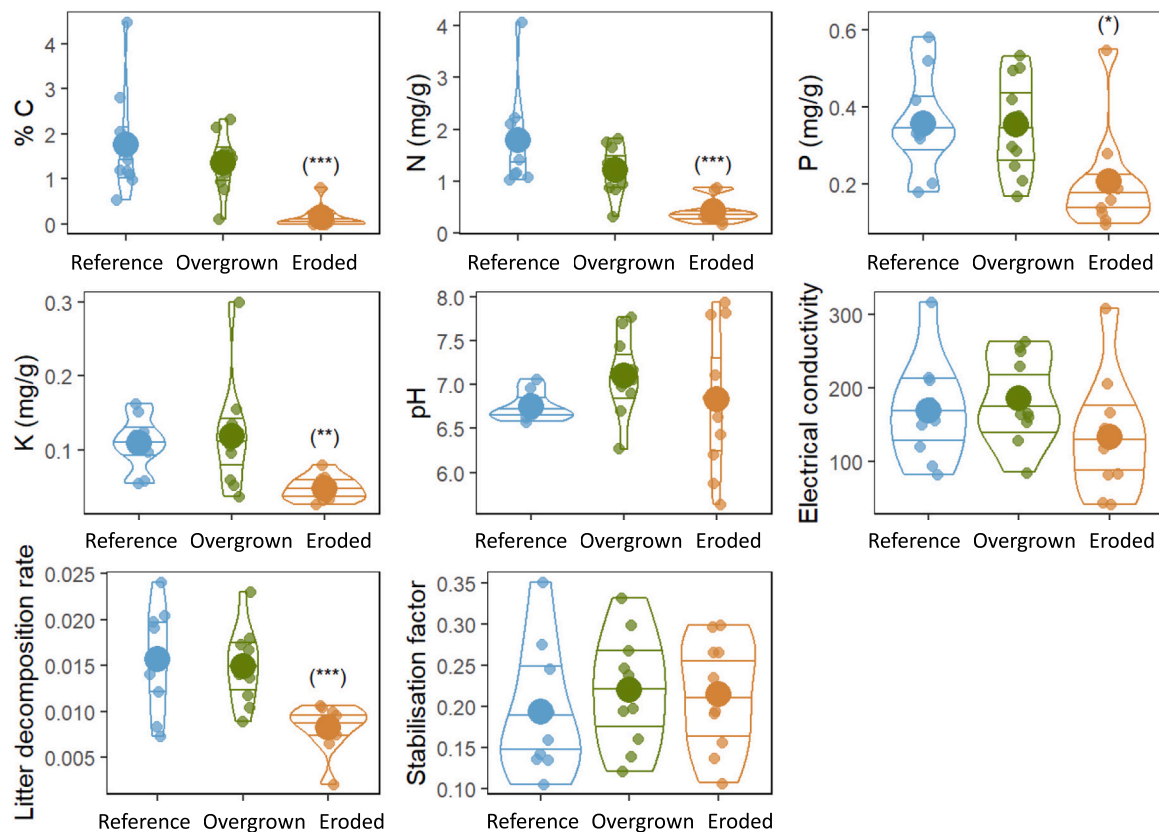


Fig. 2. Violin plots of soil organic carbon content (% C), total nitrogen (N), total phosphorus (P), available potassium (K), pH, electrical conductivity, litter decomposition rate (k) and stabilisation factor (S) in the three conservation states of drove roads (eroded, overgrown and reference). Means are depicted as bigger points and asterisks indicate significant differences at the $p < 0.05$ (*), $p < 0.01$ (**), and $p < 0.001$ (***) level according to GLMs.

relevant issue with implications at the landscape scale.

4.1. Litter decomposition, soil fertility and enzyme activities in abandoned overgrown drove roads

Our findings indicate that the better preservation of drove roads and their associated semi-natural grasslands is linked to greater soil fertility and enzyme activity. This is similar to previous studies that have demonstrated that areas characterized by traditional moderate grazing experience a reduction in soil organic matter and changes in soil structure when this practice is abandoned (Peco et al., 2006), leading to reduced nutrient availability (Oggioni et al., 2020), and altered floristic composition. Furthermore, Farris et al. (2010) discovered that the abandonment of grazing in a pastureland resulted in a decrease in soil organic matter and carbon, as well as a reduction in total nitrogen. Similarly, Fernández-Guisuraga et al. (2022), found that short- and long-term abandonment of transhumant grazing in mountain grasslands of northern Spain negatively impacted soil fertility, as well as biodiversity and forage production functions. This can be attributed to the loss of processes like defoliation, trampling, and fertilization.

Our results support the idea that traditional transhumant grazing improves the fertility and functioning of grassland soils. However, some soil variables, like the percentage of carbon, total nitrogen, available phosphorus, or litter decomposition rate, did not show significant differences between the reference and overgrown abandoned drove roads in our study. The lack of response of soil carbon to livestock use abandonment has also been observed by Fernández-Guisuraga et al. (2022) and may be attributed to the low grazing pressure characteristic of extensive and transhumant grazing, as well as the time scale at which soil carbon sequestration occurs (Medina-Roldán et al., 2012; Shrestha and Stahl, 2008). Additionally, one limitation of our study is that we did

not consider the depth-dependent response of soil organic carbon (Chen et al., 2022), which could be addressed in future analyses. Regarding the similarity in litter decomposition rate between reference and overgrown abandoned plots, previous studies have shown that the cessation of management can increase above-ground plant biomass and promote decomposition activity in grasslands (Bohner et al., 2019). The characteristics of the community of decomposer microorganisms are also important and can affect the process of litter decomposition (van Ekeren et al., 2022), therefore, future assessments of soil microorganisms as indicators could help to uncover differences between the two drove roads states.

We also demonstrated that drove roads suffering from grazing abandonment and biomass accumulation exhibited consistently lower activity levels of S, N and P-related enzymes compared to reference drove roads. This finding is consistent with previous investigations conducted by Aldezabal et al. (2015) and Oggioni et al. (2020), who reported reduced enzymatic activity in response to grazing abandonment in temperate semi-natural grasslands. Oggioni et al. (2020) attributed this phenomenon to the lack of manure inputs associated with grazing abandonment, which serves as a key driver of lower C, N and P-related enzyme activity. In our study, the tight correlation observed between soil organic carbon and enzyme activity, and their positive association with the conservation state of drove roads, suggests that the fertility and functioning of soils can be used as complementary indicators of soil conservation state in traditionally managed grasslands.

Moreover, considering that extracellular enzymes were more useful to distinguish across management types, our results underscore the importance of evaluating soil enzymes as a reliable and easy-to-measure indicator of the health state of traditional grasslands. Although we selected a subset of enzymes representative of extracellular enzyme activity (Bell et al., 2013), future research should also consider assessing

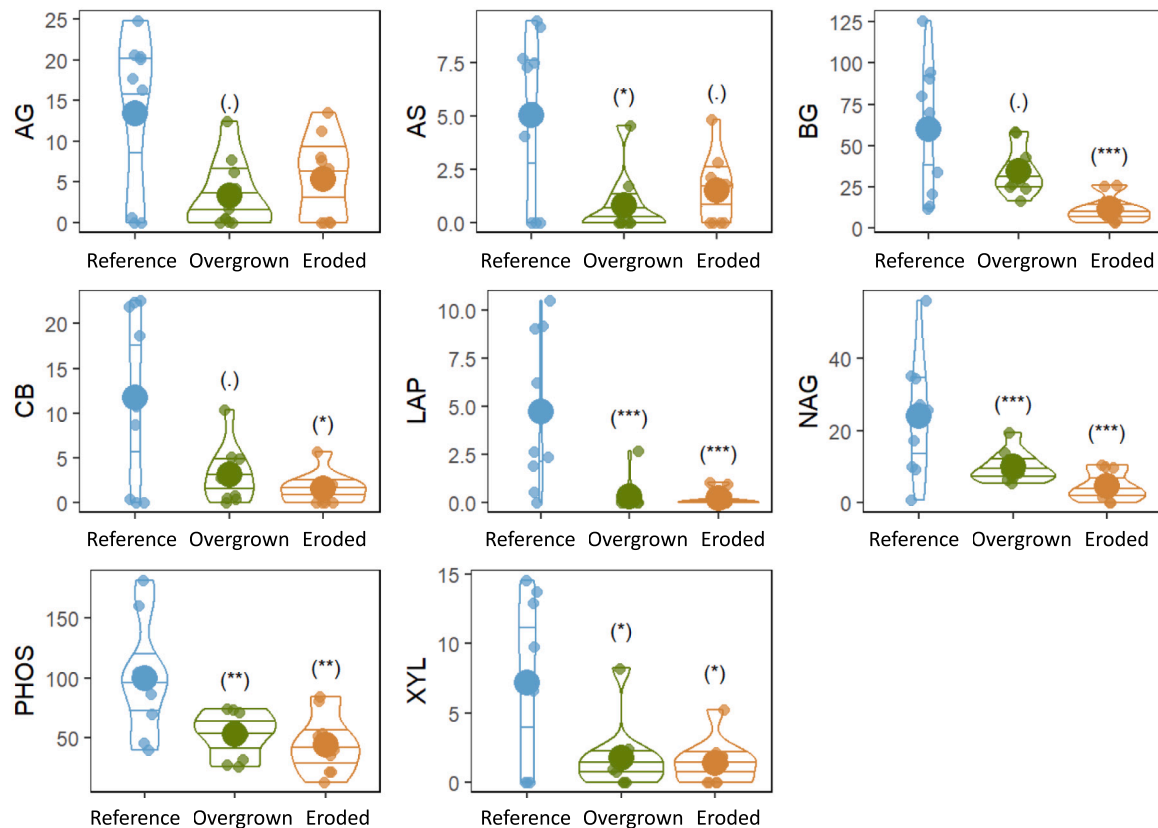


Fig. 3. Violin plots of soil enzyme activities (AG = α -glucosidase, AS = arylsulfatase, BG = β -glucosidase, CB = β -cellobiohydrolase, LAP = leucine aminopeptidase, NAG = N-acetyl- β -glucosaminidase, PHOS = phosphatase and XYL = β -xylosidase) in the three conservation states of drove roads (eroded, overgrown and reference). Means are depicted as bigger points and asterisks indicate significant differences at the at the $p < 0.05$ (*), $p < 0.01$ (**), and $p < 0.001$ (***) level according to GLMs.

oxidative enzymes such as phenol oxidase and peroxidase, which play crucial roles in important soil dynamics and are especially involved in soil organic matter storage (Sinsabaugh, 2010). Another noteworthy finding from our study is the considerable heterogeneity observed among the reference drove roads, which implies that the abandonment of these traditional routes entails not only changes in soil properties but also a reduction in the diversity of available conditions.

4.2. Litter decomposition, soil fertility and enzyme activities in eroded drove roads

Soil erosion, which is recognized as a major threat to soil health globally (Borrelli et al., 2017), was identified as a significant driver of soil degradation in our study area. The decline in vegetation ground cover exacerbates soil erosion by wind, promotes soil crusting and compaction, and leads to fertility loss through a decrease in soil organic carbon and total nitrogen (Lal, 2015; Yong-Zhong et al., 2005). The absence of livestock grazing and subsequent decrease in organic matter content can make soils more susceptible to erosion (Peco et al., 2006). Our results confirmed the hypothesis that drove roads suffering from erosion have higher degraded soils, characterized by significantly lower amounts of nutrients and enzyme activity, and a reduced litter decomposition rate.

The lack of established vegetation in these eroded grassland trails limits root exudates and thus reduces the microbial and enzymatic activity of these soils. Six out of eight of the enzyme activities determined were significantly lower when compared to reference drove roads, as expected. β -glucosidase, a C-related enzyme involved in the process of breaking down plant litter, was significantly different when compared to

reference plots, which may be explained by the lack of C inputs from plant biomass. The absence of dung inputs may also explain the low activity of N-related enzymes (N-acetyl- β -glucosaminidase, leucine aminopeptidase), which were up to four times lower than the values registered in reference drove roads. Furthermore, the negative correlation between eroded plots and all the parameters measured to assess the quality of drove road soils, and the low correlation with other conservation states, reinforces the idea that these soils are the most degraded.

While many studies have assessed the consequences of erosion in grassland soils in the context of overgrazing (Dong et al., 2022; Zhou et al., 2010), our case study documents the opposite effect: the absence of the main activity of drove roads, transhumant herd movements, led to a land use change which triggered the degradation of grassland vegetation, as motorized traffic is only possible if drove roads lose their main pastoral use. The reintroduction of light-grazing has proven to be beneficial in reducing soil erosion (Yu et al., 2019), and therefore, in addition to banning motorized traffic, recovering traditional transhumant grazing should be a priority to improve the health of drove road soils.

4.3. Ecological implications at the landscape scale

Soil properties, like some of those assessed in this study, enable soils to perform various ecological functions and provide numerous ecosystem services (Adhikari and Hartemink, 2016). Grassland soils, when preserved, are particularly important for the provision of forage for livestock and for mitigating climate change through carbon sequestration (Iepema et al., 2022; Soussana et al., 2010). The loss of soil nutrients like N, C or P, directly affects plant growth and biomass

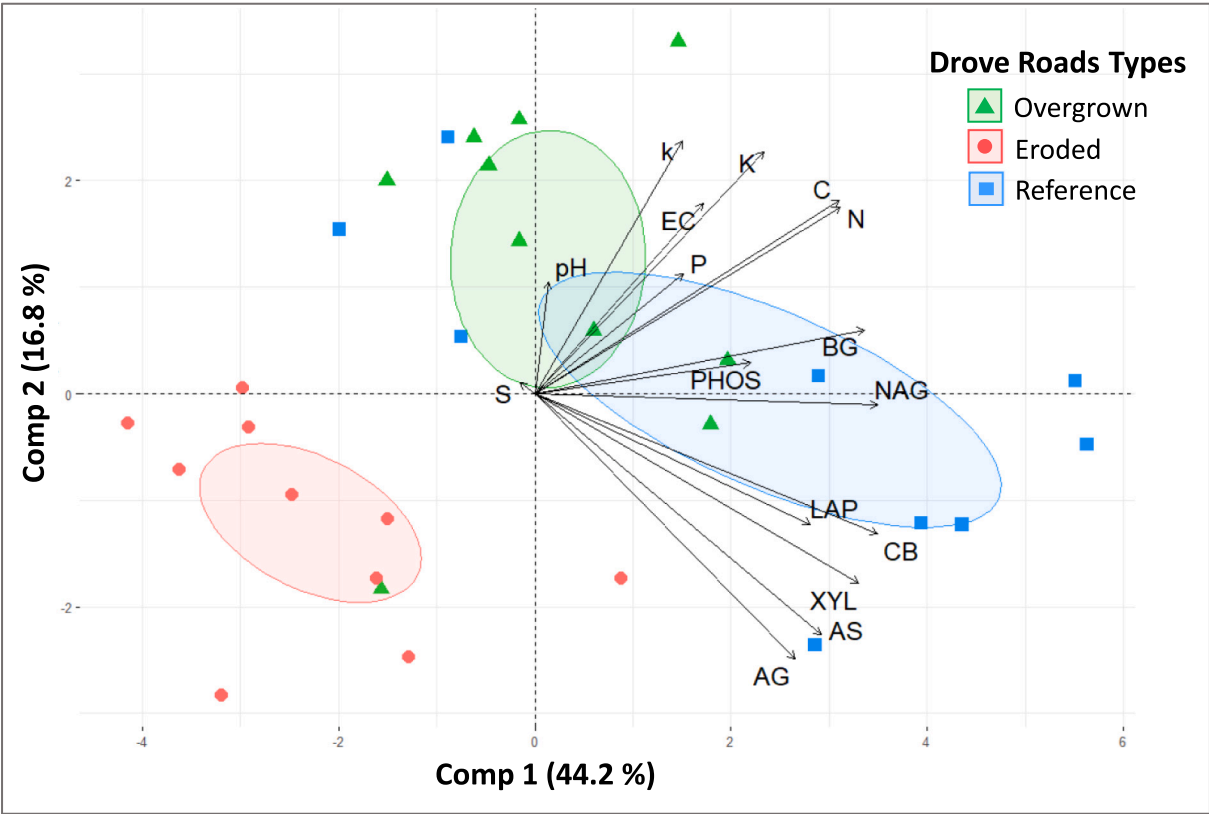


Fig. 4. Principal Component Analysis (PCA) performed on the soil variables (% C, total N and P, available K, pH, EC, litter decomposition rate (k), stabilisation factor (S) and extracellular enzyme activity) for the three drove road types (reference, overgrown and eroded).

Table 2
Component matrix showing the correlations between variables and PCA dimensions. The four higher variable loadings of each component are in bold.

Soil variables	Components	
	1	2
% C	0.797	0.467
Total N	0.798	0.449
Total P	0.389	0.288
Available K	0.599	0.583
pH	0.035	0.269
EC	0.441	0.458
S (stabilisation factor)	−0.038	0.027
k (litter decomposition rate)	0.387	0.608
AG (α-glucosidase)	0.681	−0.638
AS (arylsulfatase)	0.750	−0.580
BG (β-glucosidase)	0.862	0.154
CB (β-cellobiohydrolase)	0.897	−0.338
LAP (leucine aminopeptidase)	0.721	−0.315
NAG (N-acetyl-β-glucosaminidase)	0.897	−0.027
PHOS (phosphatase)	0.564	0.074
XYL (β-xylosidase)	0.846	−0.457

production (Fayiah et al., 2019) and the reduction in soil enzyme activity impacts essential biogeochemical cycles. Therefore, the degradation of soil in these livestock routes entails the loss of several associated ecosystem services and functions.

Maintaining well-preserved grasslands through traditional land-management practices is essential to ensure the enormously high species-diversity of these ecosystems, both in terms of plant assemblages and animal communities (Klein et al., 2020; Petermann and Buzhdygan, 2021). Specific practices like transhumant grazing are fundamental to shape open landscapes like grasslands or heathlands and preserve not only their biodiversity but also their cultural value (Liu et al., 2007;

Morán-Ordóñez et al., 2013; Oteros-Rozas et al., 2013). Accordingly, identifying which factors contribute to adequately preserve grassland soils is fundamental to guarantee their long-term sustainability. In this study, we found that two processes that are to some extent antagonistic, namely the excessive accumulation of biomass due to the cessation of grazing and the loss of vegetation cover through erosion, led to a similar loss of soil quality within the Madrid drove road network. This is coherent with the results of Fernández-Guisuraga et al. (2022), which proved that the long-term absence of moderate grazing negatively impacted ecosystem multifunctionality of mountain grasslands.

Considering the vast surface covered by this network of corridors (almost 1 % of the Spanish national territory), its conservation can have ecological implications at the landscape scale. Well-preserved drove road soils can act as biodiversity reservoirs, where the seeds dispersed in the sheep’s wool (Manzano and Malo, 2006) can thrive, and as ecological corridors, increasing grassland habitat availability within intensified and homogeneous landscapes. The present study faces a limitation in its geographical scope, as all the livestock routes selected for this research are located on the arkose substrate layer of the Madrid region. However, the extensive length of the drove road network, which goes through diverse climates and environments within the Mediterranean basin, presents an opportunity for future research to investigate the impact of drove road conservation state on soil quality across different substrate layers.

5. Conclusions

The Spanish network of drove roads constitutes a unique semi-natural habitat of considerable ecological importance, dependent on the practice of transhumant grazing for its preservation. The abandonment of this practice has adverse consequences for the edaphic ecosystem, as evidenced by the Madrid network. Our findings indicate

that the cessation of livestock use along drove roads negatively influences soil characteristics, such as nutrient content, litter decomposition, or enzyme activity, in both degradation states examined. As we hypothesized, drove roads suffering from erosion exhibited the poorest soil quality and fertility, as along with reduced litter decomposition and enzyme activity. In contrast, overgrown abandoned drove roads were characterized by substantially low enzyme activity levels but similar soil fertility, compared to reference drove roads with local grazing. This degradation process undermines the capacity of these natural corridors to provide semi-natural grasslands with soils of good quality that are involved in the production of ecosystem services like biomass production or carbon sequestration, instead of soils prone to compaction and nutrient loss. Considering the vast extension of the drove road network, that covers 0.8 % of Spain's territory and connects natural areas of high ecological value within intensified agricultural landscapes, recovering transhumant extensive grazing can serve as an essential soil conservation tool.

Data availability statement

Data will be made available on request.

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Credit authorship contribution statement

Paula Solascasas: Conceptualization, Formal analysis, Investigation, Methodology, Software, Writing – original draft, Writing – review & editing. **Violeta Hevia:** Conceptualization, Funding acquisition, Investigation, Methodology, Project administration, Supervision, Validation, Writing – review & editing. **Raúl Ochoa-Hueso:** Investigation, Methodology, Resources, Supervision, Validation, Writing – review & editing. **Francisco M. Azcárate:** Conceptualization, Funding acquisition, Investigation, Methodology, Project administration, Supervision, Validation, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.apsoil.2024.105308>.

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