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Rehabilitation of a degraded acid Mediterranean soil after 11 years of by-product calcium amendments and pasture improvement

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Abstract

The clearing of natural vegetation and tillage for agricultural purposes makes acid soils highly vulnerable to degradation, resulting in significant losses of soil fertility and crop productivity. This work focused on nature-based agricultural solutions to rehabilitate degraded acid soils in low-resource systems. We studied after 6 and 11 years how the introduction of a legume-rich pasture replacing a natural pasture or a tilled forage crop, with and without Ca-amendment, contributed to recover the soil health, the fertility and the productivity of degraded Ultisols in Western Spain. Industrial by-products, mainly sugar foam, were used as Ca-amendment to promote circular economy. The Ca-amendment factor influenced soil chemistry to 30 cm depth, while the type of soil use affected soil organic matter (SOM) to 15 cm; and both factors had positive effects on biomass productivity. Except for pH and Ca, no interaction between factors was found. Ca-amendment increased nutrient availability and soil pH, and Al ion precipitated at 0–15 cm depth. As a result, biomass production increased by 35% relative to no Ca-amendment. Forage crop produced 66% more biomass than pastures, but this increase did not translate into an increase in SOM. In fact, the legume-rich pasture was the best option to recover soil organic C and N levels, earlier and deeper. Over the 11 years, the use of pastures and Ca-amendment enhanced biomass production stability. Relative to natural, the improved pasture did not increase plant biomass but provided higher biomass stability and quality in terms of legume abundance, which was promoted when sugar foam was applied. Pastures also favoured key biological variable as earthworm's population, increasing it by four times with respect to forage crops. Compared to the non-amended and unfertilized natural pasture out of the experiment, the use of improved pasture, followed by natural pasture, combined with sugar foam and fertilization enhanced soil health, soil fertility and biomass production stability. Thus, this solution has proven effective for restoring degraded acid soils, promoting diversity and mitigating climate change, while offering a more economically beneficial alternative.

KEYWORDS

aluminium toxicity, legumes, nature-based solutions, pasture quality, productivity, tillage cease

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1 | INTRODUCTION

Acid soils have low natural fertility, which is exacerbated by the removal of natural vegetation for agricultural use and intensive tillage (Hargrove et al., 1982; McGrath et al., 2001). A good example of acid soils degraded by tillage can be found in the ancient detrital continental formations of the glaciais-piedmont type (known as 'rañas') in the southwest of the Iberian Peninsula. Rañas were formed in the Middle to Late Pliocene, with most of their properties derived from a pre-Quaternary climate with subtropical features. Nowadays, they support highly weathered and acid soils (Espejo, 1987). The climax vegetation is a cork oak forest (*Quercus suber* L.), and the soils developed under this vegetation are plinthic Palehumults (Soil Survey Staff, 2014) or Hyperdistric Acrisols (Espejo, 1987; IUSS Working Group WRB, 2007). In the 1910s to 1930s, much of this natural vegetation was cleared to cultivate rye (*Secale cereale* L.), as well as woody crops such as olive trees or vineyards. Cultivation promoted nutrient exportation and dramatically reduced the input of organic residues into the soil, and through ploughing increased the rate of the soil organic matter (SOM) mineralization, which led to a severe loss of SOM (Chaplot & Smith, 2023; Reicosky et al., 1997; Sarker et al., 2018). As a result, after several decades, soils evolved into Palexerults (Espejo, 1987; Mariscal-Sancho et al., 2009). The loss of SOM resulted in rapid soil health degradation and the release of Al forms previously locked in the organic compounds. Increased Al toxicity, driven by increased Al ionic activity and decreased $\text{Ca}^{2+}/\text{Al}^{3+}$ ratio (Gómez-Paccard et al., 2013; Peregrina et al., 2006), together with the limited nutrient bioavailability, enhanced by the extraction of base cations by crops, further reduced the already low productivity of these soils (Hontoria et al., 2018). Consequently, most crop fields were abandoned 40–100 years after clearing, but they were in such a state of degradation that self-recovery to natural vegetation became very difficult (Mariscal et al., 2007; Mariscal-Sancho et al., 2009). In these degraded and uncultivated areas, low-quality pasture poor in legumes were naturally established (Mariscal-Sancho, 2008). Over time, this pasture became invaded by a thicket mainly consisting of *Cistus ladanifer* L., *Erica umbellata* L., *Erica australis* L., *Arbutus unedo* L., and *Halimium ocymoides* Lam., further reducing the productive potential of these historically deprived areas.

Solutions need to be found to improve the functionality of these degraded acid soils, enhance ecosystem services, and provide income opportunities for the inhabitants. Compared to tilled crops, the use of pastures is a nature-based solution that increases biodiversity (Reidsma et al., 2006), improves soil health (Thapa et al., 2018) and offers an economic alternative through its use by livestock

and wild animals, as hunting is common in the area. Furthermore, pastures have the potential to mitigate climate change (Martens et al., 2004). Regarding to the soil, pastures prevent soil disturbance, protect the soil surface through a permanent cover and promote dense and deep living root systems that stimulate soil biota, enhance aggregation and porosity and increase SOM stocks (Karlen et al., 1999; Martens et al., 2004; McNally et al., 2015). However, to enhance the potential benefits of pastures through adequate productivity in these degraded acid soils, liming would be necessary to increase pH and reduce soil Al^{3+} , as it inhibits root growth, thereby increasing productivity as well as species richness (Abdalla et al., 2022; Goulding, 2016).

Liming of acid soils is a widely used agronomic practice that brings multiple benefits to agriculture and environment (Holland et al., 2018). In the soils of the study area, the ability of different by-products, such as sugar foam, red gypsum and dolomitic converter residue, to increase pH and reduce Al toxicity has been demonstrated in annual forage crops (Gómez-Paccard et al., 2013; Hontoria et al., 2018; Peregrina et al., 2006; Peregrina, Mariscal, & Espejo, 2008; Peregrina, Mariscal, Ordóñez, et al., 2008). The richness of these by-products in other nutrients besides Ca (Peregrina et al., 2006) and especially Mg contributes to increase fertility and avoid Mg deficiencies which could be one of the main drawbacks of conventional liming (Panhwar et al., 2020). Therefore, the use of these industrial by-products as readily available, low-cost liming materials would not only improve soil health and enhance profitability but also promote circular economy practices. However, it is not well known to what extent the effect of such by-product-based Ca-amendments might be different in the long-term on non-tilled pastures compared to an annual tilled forage crop and what effect it might have on soil C accumulation (Abdalla et al., 2022; Gibbons et al., 2014).

In addition to liming, proper plant nutrition requires improving soil nitrogen levels, which would benefit from increasing the proportion of legumes in the pasture. A legume-rich pasture enhances the biological fixation of atmospheric nitrogen, thereby enriching the soil and biomass with nitrogen (Spehn et al., 2002). An improved pasture with an appropriate mixture of grasses and legumes would contribute to increased yields, enhanced SOM content, increased soil health, increased above- and below-ground diversity (Dhakal & Islam, 2018; Hernández-Esteban et al., 2019; Moreno et al., 2021; Wu et al., 2017), so it has been proposed to rehabilitate degraded naturalized pastures (Bouman et al., 1999). As legumes have a better response to liming than grasses (Li et al., 2019), enriching pastures with legumes would reinforce the positive effect of liming on biomass production.

It would also contribute to a more lasting effect as short-lived effects of liming on yield have been attributed to the depletion of soil N reserves (Holland et al., 2018). It remains to be confirmed that legume-rich pasture improves the response to liming in the long-term compared to naturalized pasture.

Therefore, improving the performance of naturalized pastures through the application of Ca-amendments and the introduction of new species, mainly legumes, is proposed to enhance biomass production and the feeding of both domestic and wild fauna in this area. This approach would also improve soil health, promote biodiversity and mitigate climate change. Additionally, it would result in higher economic performance for farmers and ranchers in the area, as the investment made in amending the soil with Ca-rich by-products is recovered in less than 2 years (González-Fernández et al., 2012). As some of the impacts of liming are context-dependent and far-reaching, more long-term studies are needed (Holland et al., 2018). In particular, it should be clarified if, compared to a legume-poor naturalized pasture, a legume-rich pasture could enhance and maintain in the long-term the beneficial impacts of liming on soil and pasture parameters.

In this work, we studied how the introduction of improved pastures, replacing natural pastures or an annual forage crop, with and without by-product based Ca-amendment, contributed to the recovery of these degraded acid soils. To do this, we assessed over 11 years the effects on soil and plants of six different management strategies: three types of soil use—natural (without tillage) and improved (without tillage, seeded with a mixture of selected legume and grass species) pastures, and an annual tilled forage crop—combined with or without the application of a by-product based Ca-amendment. For this purpose, we selected several soil parameters, such as pH, Al^{3+} , exchangeable base cations, total and particulate organic carbon, total nitrogen, C/N ratio and earthworm population, that were assessed 6 and 11 years after the start of the experiment. Additionally, we evaluated crop parameters, such as total and legume biomass production in pastures.

2 | MATERIALS AND METHODS

2.1 | Experimental site

The study was conducted at the Cañamero's Raña (SW Spain), a broad glaciis–piedmont plateau that occupies a very large flat area (more than 25,000 ha with a slope less than 1% slope). According to the Köppen classification, the climate is temperate with dry and hot summer (Csa). Mean annual temperature is 15.3°C with the lowest mean temperature in January (6.2°C) and highest in August (25.2°C). Mean annual evapotranspiration (Penman–Monteith) is 1365 mm, with the lowest value in December (20 mm) and the highest in July (234 mm). The mean annual precipitation is 878 mm, with the lowest mean monthly precipitation in July and August (6.0 and 10.7 mm, respectively) and the highest from October to January (121.6, 109.5, 114.5 and 120.7 mm, respectively). Monthly precipitation had high inter-annual variability during the study (Hontoria et al., 2018). According to Soil Taxonomy, soils are clay skeletal, kaolinitic, acid, thermic Plinthic Palexerults (Soil Survey Staff, 2014), with the following characteristics: kaolinite as the dominant mineral in the clay fraction, low pH that decreases with depth, low content of exchange bases and the exchange complex dominated by Al; they also have high content in weathered quartzite rock fragments (Table 1).

The study area was traditionally cropped with rye from the early 1950s until 1987. From 1987 to 1997, it was cultivated sporadically every 4–5 years, and since then, it has remained fallow until the beginning of the present experiment. A natural pasture and isolated specimens of *Halimium ocymoides* L. and *Cistus ladanifer* began to establish. In the area, the natural pasture (NP) is of very poor quality; its most common species are *Vulpia bromoides* (L.) S.F. Grey (+++), *Molinierella laevis* (Brot.) Rouy (+++), *Briza maxima* L. (++), *Briza media* L. (++), *Holcus lanatus* L. (+), *Bromus tectorum* L. (+), *Anthoxanthum aristatum* Boiss (++), *Anarrhinum bellidifolium* L. Wild (+), *Rumex acetosella* L. (+++), *Rumex bucephalophorus* L. (++), *Plantago coronopus* L. (+++), *Plantago bellardi*

TABLE 1 Representative soil profile in the study area at the beginning of the experiment.

Horizon	Depth	Rock	Sand	Silt	Clay	SOM	pH _{water}	Al^{3+}	Ca^{2+}	Mg^{2+}	Na^+	K^+
	cm	fragments %	2000– 50 µm	50–2 µm	<2 µm	%	1:2.5	cmol _c kg ⁻¹				
Ap	0–25	52	80	6	14	3.4	5.3	0.72	1.12	0.21	0.05	0.65
AB	25–35	47	69	6	25	1.6	5.0	1.01	0.85	0.16	0.04	0.08
Bt	35–90	56	60	5	35	0.3	4.9	1.75	0.82	0.11	0.03	0.07

Note: Rock fragments (>2 mm).

Abbreviations: Al^{3+} , KCl-extractable Al; Ca^{2+} , Mg^{2+} , Na^+ , K^+ , Cations extracted with ammonium acetate buffered at pH 7.0; SOM, soil organic matter.

L. (++) (where +, ++ and +++ represent the relative abundance of each specie in crescent order) (Mariscal-Sancho, 2008). The legume species, *Ornithopus compressus* L., *Anthyllis lotoides* L., *Trifolium campestre* Schreb., *Trifolium arvense* L. and *Trifolium tomentosum* L., are scattered and constitute less than 2% of the pasture biomass (Mariscal-Sancho, 2008).

2.2 | Experimental design

The field experiment was established in 2002 using a split-plot randomized block design with four replications. The main factor was the application (A) or not (NA) of a sugar foam waste as Ca-amendment (factor Ca). This by-product is obtained from the sugar production from sugar beet and is rich in calcium carbonate, especially active limestone, making it an important source of Ca and to a lesser extent Mg, as well as other nutrients (Peregrina et al., 2006). The secondary factor was the soil use and management (factor SU): two types of pastures, no-tilled natural pasture (NP) and no-tilled improved pasture (IP), versus a conventionally tilled forage crop (FC). Thus, each main plot was split into three subplots ($12 \times 6 \text{ m}^2$ each) (Figure 1) to accommodate the secondary factor levels, which made a total of 24 subplots. At the beginning of the experiment, a first dose of sugar foam waste (SF) was manually applied to amended plots at a rate of 3.9 Mg of dry product ha^{-1} , a calculated dose to raise the pH to 6.2. All the plots (amended or not) were tilled using two passes with walking tractor up to 25 cm and a power tiller for the upper 5 cm. The plots with pastures did not receive any further work afterwards. A second application of SF amendment was done in October 2010 before seeding at a rate of 2.5 Mg of dry product ha^{-1} . This time, the Ca-amendment was incorporated to the soil only in the amended forage crop plots, whereas in amended pasture plots, it was left at soil surface. In order to balance the Ca/Mg ratio in amended plots, 100 kg ha^{-1} of MgO from dolomite converter basic slag, an efficient Mg amendment

(Peregrina, Mariscal, Ordóñez, et al., 2008) was added in 2003 and 2010 along with 100 kg ha^{-1} of MgO in the form of MgSO_4 . According to Gómez-Paccard et al. (2013), the main components of the sugar foam waste (in g kg^{-1}) were CaO: 437; organic matter: 86.7; MgO: 47.3; Al_2O_3 : 24.2; SiO_2 : 17.3 and P_2O_5 : 8.1, with a total calcium carbonate equivalent of 765 and 213 g kg^{-1} of calcium carbonate reactive with ammonium oxalate ('active lime'). The main components of dolomite converter basic slag were CaO: 395 g kg^{-1} and MgO, 401 g kg^{-1} .

Annual soil management in the tilled forage crop plots involved two passes with a walking tractor prior to sowing. Seeds were hand-applied at a rate of 140 kg ha^{-1} and then buried with a shallow power tiller pass (5 cm deep). The seed mix varied over the years: in 2002–2003, it comprised *Secale cereale* L. (57%), *Triticosecale* (17%) and *Vicia sativa* L. (26%); in 2003–2005, it was *Triticosecale* (74%) and *Vicia sativa* L. (26%); in 2005–2006, it was *Avena sativa* L. (74%) and *Vicia sativa* L. (26%); and from 2006 to 2015, it consisted of *Avena sativa* L. (57%), *Triticosecale* (17%) and *Vicia sativa* L. (26%).

The new species introduced to improve the pasture were selected based on recommendations from the Agricultural Research Institute of Extremadura Finca La Orden-Valdesequera, following a preliminary field test. These species included: *Trifolium vesiculosum* L. 'Zulu' variety, *Trifolium subterraneum* L. 'Dalkeith' variety, *Trifolium subterraneum* L. 'Seaton Park' variety (2 kg ha^{-1} each), *Trifolium michelianum* var. *balansae* (Boiss.), *Biserrula pelecinus* L. 'Casbah' variety, *Ornithopus compressus* L. 'Avila' variety (3 kg ha^{-1} each), *Lolium rigidum* Gaud 'Winnmera' variety and *Dactylis glomerata* L. 'Curie' variety (4 kg ha^{-1} each). In October 2002, seeds were manually distributed in the IP treatment and incorporated into the soil surface to a depth of 2 cm using a rake. Subsequently, the soil surface was rolled to facilitate seed germination. The NP treatment was spontaneously established.

During the first campaign, FC plots were hand-fertilized with 70 kg N ha^{-1} , 70 kg P ha^{-1} and 70 kg K ha^{-1}



FIGURE 1 Partial view of the experimental field during the sowing of the forage crop (Cañamero, Spain).

in autumn, and with 35 kg N ha⁻¹, 70 kg P ha⁻¹ and 70 kg K ha⁻¹ in subsequent years. Both NP and IP treatments initially received the same fertilizer doses as FC in autumn, but in subsequent years, they were only fertilized with P and K at the same doses as in FC. At maturity each year (~July), the crop was manually harvested at 20 cm above the soil surface.

2.3 | Soil and plant sampling and analysis

At 6 and 11 years after the start of the experiment, three disturbed soil samples were collected in October from each plot and composited from depths of 0–5, 5–15 and 15–30 cm. Additionally, to compare with the natural pasture conditions outside the fenced area (non-amended, unfertilized, non-protected against sheep flocks and wild fauna), we collected four composite soil samples on the outside of the experimental field, 5 m from the perimeter fence and aligned with the centre of the four study blocks. These samples were labelled as 'non-amended unfertilized natural pasture'.

All soil samples were air dried and sieved (<2 mm). Subsamples of fine earth were analysed for total organic carbon (TOC), particulate organic carbon (POC), total nitrogen (N), pH, exchangeable base cations and Al³⁺. TOC and N were determined using an elemental CN analyser (LECO Trumac1) and C/N ratio was calculated by dividing TOC by N. POC was determined according to Cambardella and Elliott (1992). Soil pH was determined in de-ionized water (1:2.5 soil/water ratio). Exchangeable base cations, including Ca²⁺, Mg²⁺, K⁺ and Na⁺ (referred to as Ca, Mg, K and Na in the text), were extracted with ammonium acetate at pH 7 and then determined by atomic absorption spectrophotometry. The Al³⁺ (Al in the text from now on) was extracted with 1 M KCl and determined by titration (Soon, 1993).

Earthworms were also collected from each plot in 2008 and 2013. In 2008, earthworms were manually collected in October from a surface prism of 15 × 15 × 10 cm³, size, whereas in 2013 they were taken at the end of April 2013 from a surface prism soil of 20 × 20 × 10 cm³ size; earthworms also were manually collected from the four points with natural pasture out of the fence.

From 2003 to 2013, plant biomass was annually collected from each plot at harvest time, using two random 1 × 1 m² squares as subsamples from each plot. During the final campaign, the legume plants were manually separated in the biomass samples from pasture plots and the proportion of legumes was determined. Fresh weight was measured in the field, while dry weight was measured after drying the samples for 72 h at 60°C. These data were

used to determine the average annual biomass production of each plot.

2.4 | Statistical analysis

The data were statistically analysed using a general linear model for a split-plot design with blocks (Statgraphics Centurion XIX; StatPoint Technologies Inc.). In the model, Ca-amendment was considered the main factor and soil use the secondary factor, along with year of sampling and depth as fixed effects (depth was not used for earthworm and biomass production analysis). Analyses of most soil properties are shown for each depth and year independently, given that both showed interactions with study factors in most cases. Box-Cox transformations were applied as needed to fulfil ANOVA assumptions. Mean comparisons among treatments were conducted using the Fisher's least significant difference (LSD) test at a significance level of $p < .05$ unless otherwise stated.

3 | RESULTS

3.1 | Soil acidity, base cations and aluminium

After 6 and 11 years, Ca-amendment affected soil pH as well as Ca, Mg, Na, K and Al values in the exchange complex (Table 2). Soil pH, Ca and Al were the variables most strongly affected by the factors throughout the 30 cm depth. Thus, the Ca-amendment increased pH and Ca, and reduced Al at all three depths (0–5, 5–15 and 15–30 cm) and in the 2 years analysed.

The type of use affected these variables to a lesser extent than the Ca-amendment. Ca and pH showed an interaction between factors (SU × Ca), mainly at 11 years, so that the type of use affected these variables only when sugar foam was applied (Table 2). After 11 years, both pH and Ca increased in both pastures (NP and IP) compared to FC at 0–5 cm depth. At 5–15 cm depth, after 6 years, both pH and Ca also increased with NP and IP compared to FC, but these differences vanished after 11 years. Finally, at 15–30 cm depth, after 11 years, both pH and Ca decreased with NP and IP compared to FC.

The Ca values were approximately three times higher in the amended plots than in the non-amended ones at 0–5 cm depth. In the 5–15 and 15–30 cm layers, these differences reduced to double (Figure 2a,b). After 6 years, at the 5–15 cm layer of the amended plots, Ca values were higher in both pastures (NP and IP) than in FC (Figure 2a). After 11 years, Ca values were higher in both pastures (NP and IP) than in FC at the 0–5 cm depth, but in the deeper

TABLE 2 Soil pH, extractable aluminium, and exchangeable base cations as affected by soil use and Ca-amendment after 6 and 11 years of application.

Factor	pH		Al ³⁺		Ca ²⁺		Mg ²⁺		K ⁺		Na ⁺	
	6years	11years	6years	11years	6years	11years	6years	11years	6years	11years	6years	11years
0–5 cm depth												
Soil use (SU)												
Forage crop	5.78a	5.68a	0.16a	0.49a	3.10a	3.09a	0.38a	0.39a	0.38a	0.49a	0.08a	0.07a
Natural pasture	5.90a	5.74b	0.11a	0.46a	4.00a	3.38b	0.46ab	0.42b	0.51ab	0.52b	0.09a	0.06a
Improved pasture	5.92a	5.75b	0.12a	0.47a	3.94a	3.34b	0.58b	0.42b	0.56b	0.53b	0.10a	0.06a
Ca-amendment (Ca)												
Non-amended	5.59a	5.22a	0.26b	0.94b	2.10a	1.58a	0.29a	0.24a	0.45a	0.53b	0.09a	0.07b
Amended	6.14b	6.22b	0.00a	0.00a	5.26b	4.98b	0.67b	0.58b	0.52a	0.49a	0.09a	0.05a
Effects												
SU	ns	*	ns	ns	ns	**	+	**	+	+	ns	ns
Ca	*	***	***	***	*	***	**	***	ns	**	ns	*
SUxCa	ns	**	ns	ns	ns	*	ns	**	ns	ns	ns	ns
5–15 cm depth												
Soil use (SU)												
Forage crop	5.55a	5.54a	0.31b	0.56a	2.24a	2.08a	0.25a	0.31a	0.24a	0.31a	0.08a	0.05a
Natural pasture	6.00b	5.50a	0.19a	0.58b	2.96b	2.03a	0.26ab	0.30a	0.25a	0.31a	0.12a	0.04a
Improved pasture	5.96b	5.50a	0.14a	0.58b	3.01b	2.04a	0.32b	0.30a	0.26a	0.31a	0.10a	0.05a
Ca-amendment (Ca)												
Non-amended	5.46a	5.08a	0.38b	1.14b	1.49a	1.26a	0.18a	0.20a	0.23a	0.31a	0.08a	0.05b
Amended	6.21b	5.94b	0.04a	0.01a	3.99b	2.84b	0.38b	0.41b	0.27b	0.30a	0.12a	0.04a
Effects												
SU	**	ns	***	*	*	ns	+	*	ns	ns	ns	ns
Ca	***	***	**	***	*	***	**	***	*	ns	ns	*
SUxCa	*	*	***	ns	+	**	ns	*	ns	ns	ns	ns
15–30 cm depth												
Soil use (SU)												
Forage crop	5.42a	5.31b	0.51a	1.14a	1.86a	1.38b	0.12a	0.11a	0.12a	0.11a	0.06a	0.01a
Natural pasture	5.47a	5.27a	0.49a	1.05a	1.67a	1.28a	0.12a	0.11a	0.12a	0.12a	0.06a	0.01a
Improved pasture	5.43a	5.28a	0.51a	1.05a	1.78a	1.32a	0.13a	0.11a	0.12a	0.12a	0.06a	0.01a

TABLE 2 (Continued)

Factor	pH		Al ³⁺		Ca ²⁺		Mg ²⁺		K ⁺		Na ⁺	
	6 years	11 years	6 years	11 years	6 years	11 years	6 years	11 years	6 years	11 years	6 years	11 years
Ca-amendment (Ca)												
Non-amended	5.18a	4.93a	0.67b	1.69b	1.21a	0.86a	0.12a	0.11a	0.11a	0.12a	0.06a	0.01a
Amended	5.70b	5.65b	0.32a	0.47a	2.33b	1.79b	0.12a	0.11a	0.12a	0.12a	0.06a	0.01a
Effects												
SU	ns	*	ns	ns	ns	***	ns	ns	ns	ns	ns	ns
Ca	***	***	**	**	*	***	ns	ns	ns	ns	ns	ns
SUxCa	ns	***	ns	ns	ns	***	ns	ns	ns	ns	ns	ns

Note: ns, +, *, **, ***, not significant, $p < .1$, $p < .05$, $p < .01$ and $p < .001$, respectively in the ANOVA analysis. Means followed by different letters indicate significant differences between treatments within each factor for each variable and depth of study (LSD test).

layers, the Ca differences shifted. In amended FC, Ca was 3.5% and 11% higher than in amended pastures (A-NP and A-IP) at the 5–15 and 15–30 cm layers, respectively (Figure 2b).

The pH followed a similar pattern to Ca. After 6 and 11 years, up to a depth of 15 cm, pH was about one unit higher in the amended plots compared to the non-amended plots, whereas at the 15–30 cm layer, the difference reduced to 0.6 (Figure 3a,b). Like Ca, the type of use had no effect on pH in non-amended plots after 6 years. While, after 11 years, there was an effect only at the 0–5 cm depth, where pH was higher in FC than in NP. In amended plots, after 6 years at the 5–15 cm layer, pH in both pastures (NP and IP) was higher than in FC (Figure 3a). However, after 11 years, both pastures showed the highest pH values at 0–5 cm, but the lowest at the 5–15 and 15–30 cm layers (Figure 3b).

In the amended plots, after 6 and 11 years, Al was reduced practically to zero up to a depth of 15 cm and by ca. 50% and 72% at the 15–30 cm layer for 6 and 11 years, respectively (Table 2). The type of use hardly affected Al, except for a small reduction in the 5–15 cm layer in FC compared to pastures. Additionally, at this same depth, Al decreased with both pastures (NP and IP) compared to FC after 6 years; however, Al increased with NP and IP compared to FC after 11 years (Table 2).

On the other hand, Mg increased with the Ca-amendment at 0–5 and 5–15 cm layers after 6 and 11 years. Moreover, at the 0–5 cm depth, after 11 years, Mg was higher in both pastures (NP and IP) than in FC, while after 6 years, only NP was higher than FC at this same depth. The rest of the base cations (Na and K) were generally less affected by the factors and mainly at the top 5 cm. After 11 years, the Ca-amendment reduced Na to a depth of 15 cm (by ca. 30% at 0–5 cm and by ca. 20% at 5–15 cm layers) and reduced K by 8% at the 0–5 cm depth (Table 2).

Data of pH, Ca, Mg, Na, K and Al in the non-amended unfertilized natural pasture out of the fence (Table 3) were similar to that of non-amended fertilized natural pasture into the fence.

3.2 | Biomass production and legume abundance

Both the Ca-amendment and the type of use affected the mean annual aerial biomass production for the period 2002–2013 (Figure 4b), without interaction between them. The Ca-amendment increased the mean annual biomass production by 35% compared to the no Ca-amendment. The improved pasture did not increase the mean annual production relative to the natural one, whereas the production in FC was much higher (66% more) than in

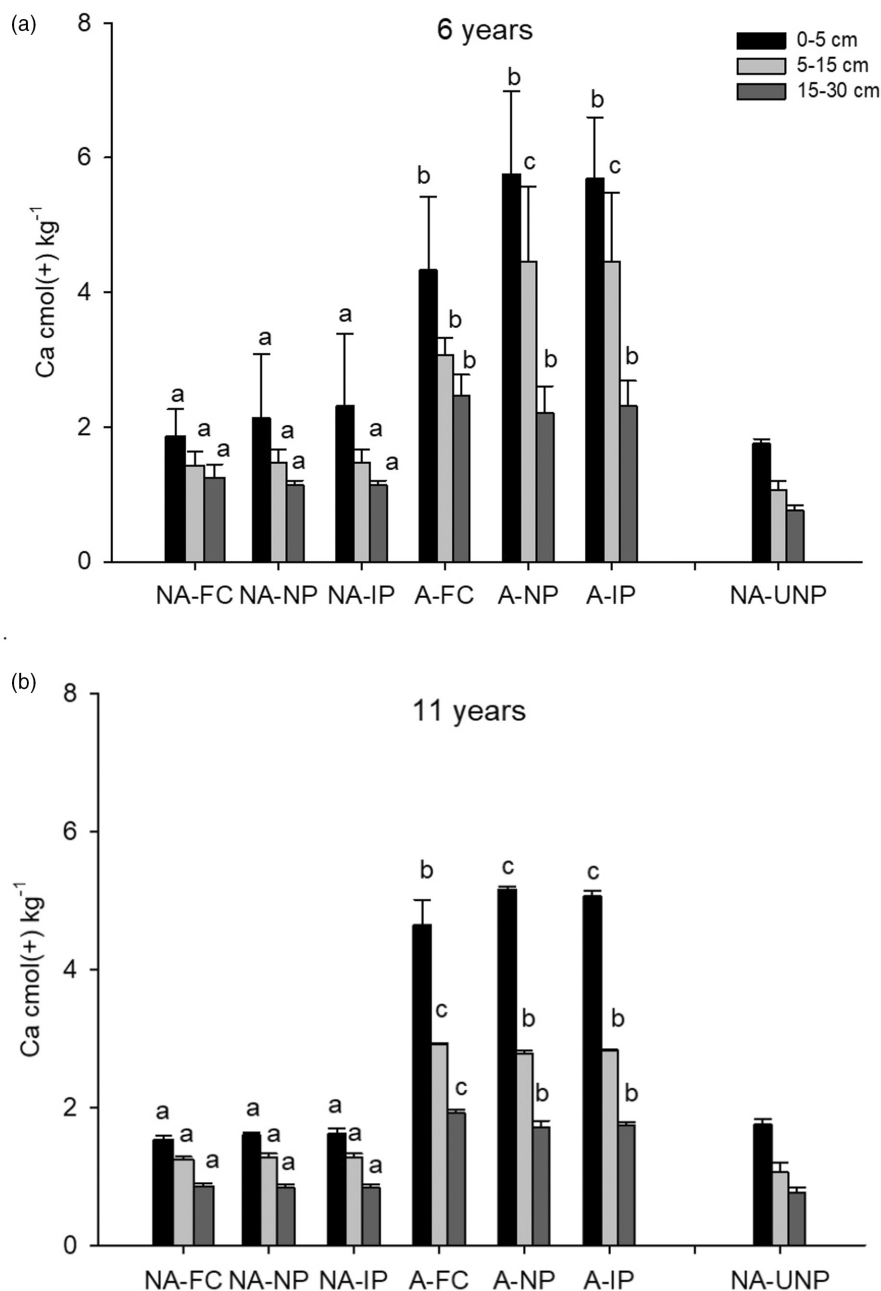


FIGURE 2 Soil exchangeable calcium concentration in the studied treatments after 6 (a) and 11 (b) years of their application. Non-amended treatments with forage crop (NA-FC), with natural pasture (NA-NP) or with improved pasture (NA-IP); amended treatments with forage crop (A-FC), with natural pasture (A-NP) or with improved pasture (A-IP); NA-UNP: Non-amended unfertilized natural pasture. Different letters indicate significant differences between treatments within each soil depth (LSD test, $p < .05$). Vertical bars indicate standard errors.

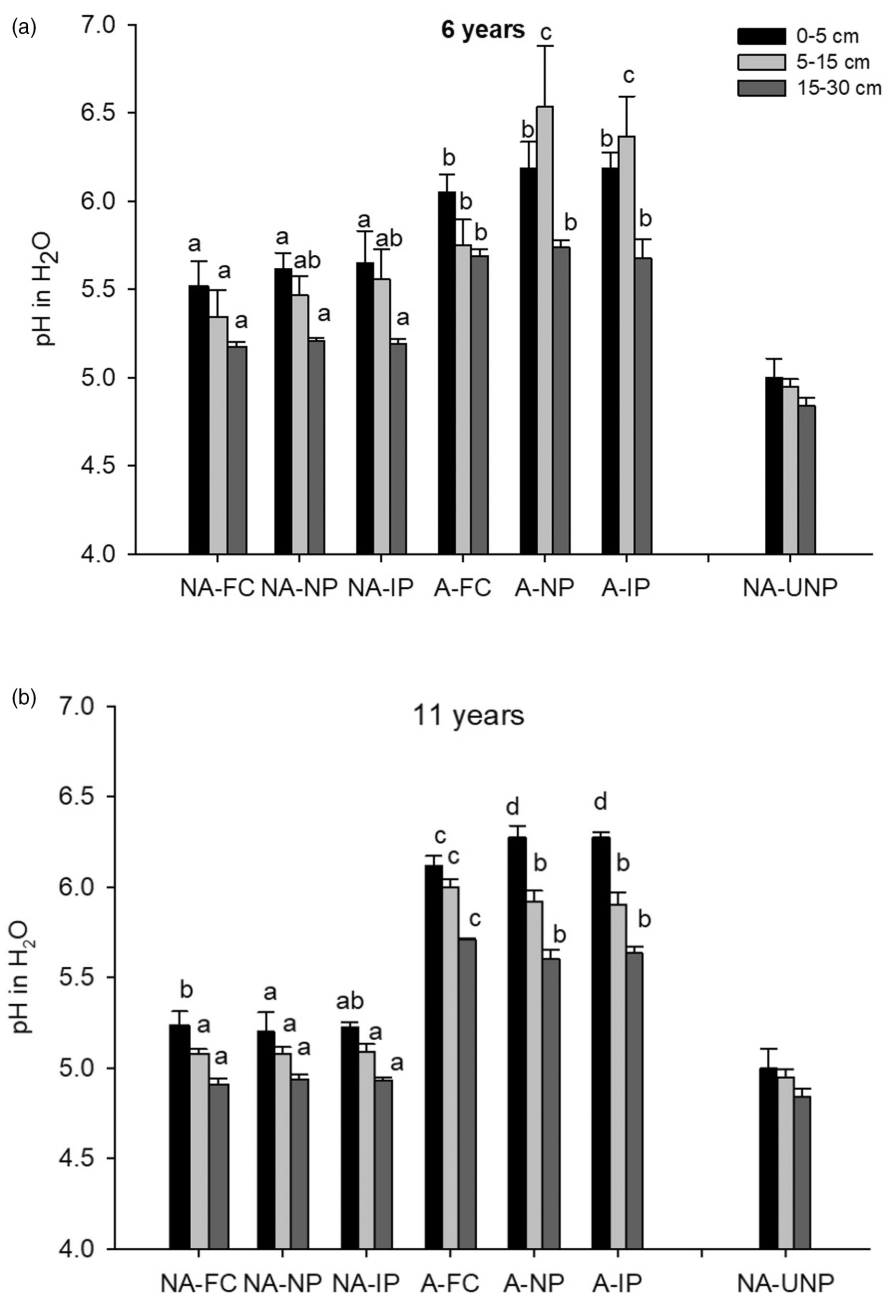
both pastures. The mean annual production in the non-amended unfertilized natural pasture (out of the fence) was 1410 kg ha⁻¹, almost 60% of that in the non-amended fertilized natural and improved pastures (2416 kg ha⁻¹).

Besides the mean annual biomass production, the stability of production is also important from the perspective of farmer incomes. Considering the coefficient of variation of the annual biomass production over the 11 years of the experiment (Table 4), the use of pastures showed more stability in production than FC. While IP reduced production variability by almost 10 percentage points compared to NP and by 20 points compared to FC, the Ca-amendment reduced production variability, especially for FC, where the coefficient of variability in the non-amended plots was

89% compared to 73% in the amended plots. In contrast, IP showed similar variability in both conditions (~60%).

The production of legume biomass in pastures (Figure 4a) was also strongly affected by the Ca-amendment and by the type of use. In the amended plots, legume biomass was 3.6 times higher than in the non-amended plots. In the improved pastures, it was 83% higher than in the natural pastures. Legume biomass accounted for 11% of the total biomass in natural pastures and 21% in improved pastures. Legumes represented 9% of total biomass in non-amended plots, 23% in amended ones and only about 1% in the non-amended unfertilized natural pasture outside the fence. The introduced legume species with the best response were *T. vesiculosum* L.

FIGURE 3 Soil pH in the studied treatments after 6 (a) and 11 (b) years of their application. Non-amended treatments with forage crop (NA-FC), with natural pasture (NA-NP) or with improved pasture (NA-IP). Amended treatments with forage crop (A-FC), with natural pasture (A-NP) or with improved pasture (A-IP). NA-UNP: Non-amended unfertilized natural pasture. Different letters indicate significant differences between treatments within each soil depth (LSD test, $p < .05$). Vertical bars indicate standard errors.



‘Zulu’ variety, *Biserrula pelecinus* L. ‘Casbah’ variety and *Ornithopus compressus* L. ‘Avila’ variety.

3.3 | Soil organic carbon and nitrogen

Six years after the experiment began, IP increased TOC and POC relative to FC by 15% and 49%, respectively, at 0–5 cm depth (Figure 5). By contrast, Ca-amendment did not cause significant differences in these variables at the two studied depths. After 11 years, both IP and NP increased TOC compared to FC by 33% and 24%, respectively, at 0–5 cm depth, whereas at 5–15 cm, only IP achieved higher TOC relative to FC. Particulate organic

C followed the order IP > NP > FC at 0–5 cm depth. The increases relative to FC were much higher in POC than in TOC: 75% and 57% for IP and NP, respectively, while IP increased POC by ~12% relative to NP. At a depth of 5–15 cm, both IP and NP increased POC by ~30% compared to FC. Ca-amendment did not cause significant differences in TOC and POC at any depth, but when the first 15 cm were considered globally, TOC was 30% higher in the amended plots than in the non-amended plots. There was no interaction between Ca-amendment and type of use for TOC and POC in any of the cases.

In terms of soil N (Figure 6), after 6 years, there were only differences due to the Ca-amendment. Thus, at 0–5 cm depth, Ca-amendment increased N by 18%

Depth		0–5 cm	5–15 cm	15–30 cm
pH _{(1:2.5)water}		5.00 ± 0.11	4.95 ± 0.04	4.84 ± 0.05
Al ³⁺	cmol ₍₊₎ kg ^{−1}	0.96 ± 0.05	1.14 ± 0.01	1.80 ± 0.18
Ca ²⁺		1.76 ± 0.07	1.06 ± 0.14	0.76 ± 0.08
Mg ²⁺		0.51 ± 0.07	0.31 ± 0.05	0.12 ± 0.02
K ⁺		0.45 ± 0.08	0.30 ± 0.04	0.15 ± 0.01
Na ⁺		0.075 ± 0.008	0.072 ± 0.006	0.031 ± 0.008
Total organic C	g kg ^{−1}	38.7 ± 2.4	32.4 ± 3.5	15.4 ± 1.4
Total N		2.2 ± 0.2	1.8 ± 0.2	0.7 ± 0.1
C/N ratio		17.1 ± 1.8	18.6 ± 1.2	21.1 ± 2.9
Earthworm density	Nb m ^{−2}	12.6 ± 1.7 ^a		

Note: Mean ± standard deviation.

^aFor a depth of 0–10 cm.

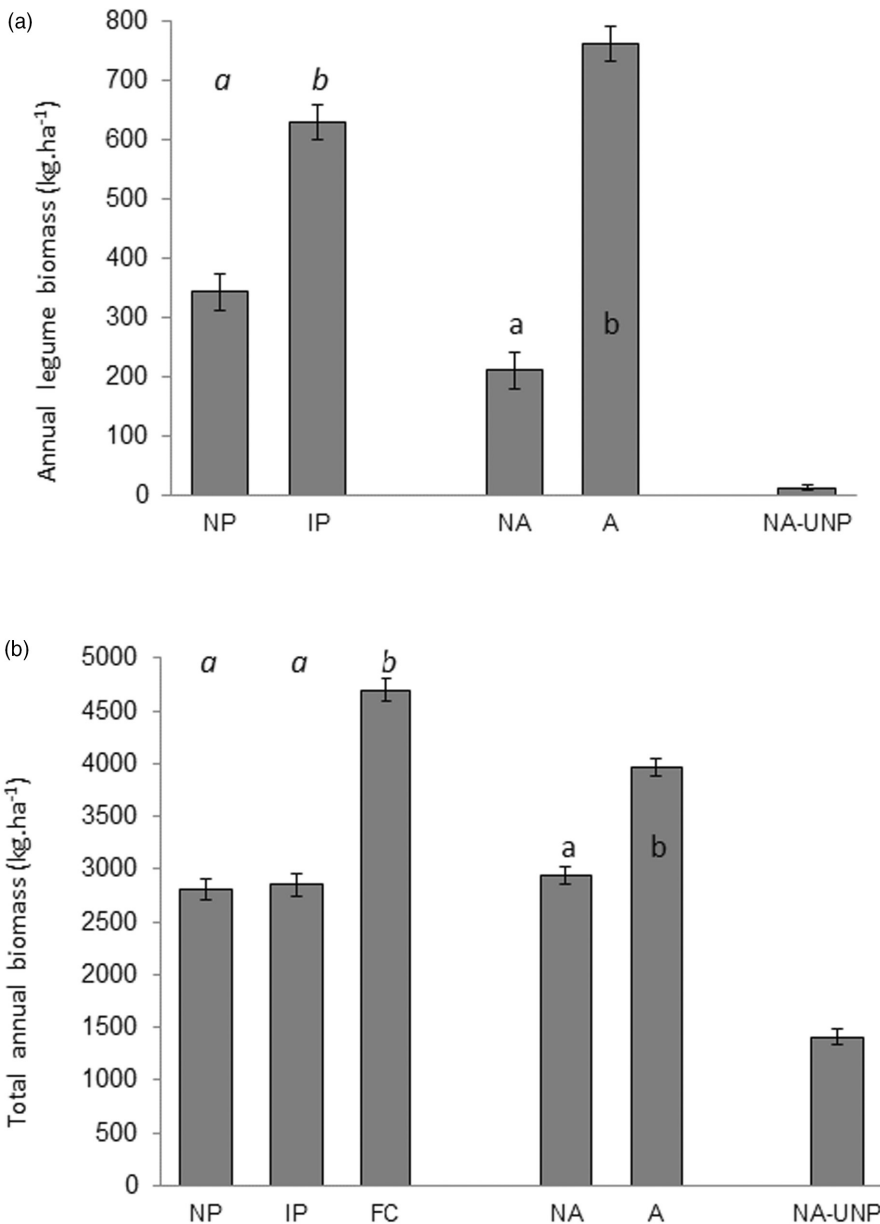


TABLE 3 Soil pH in water (1:2.5), extractable Al (KCl), exchangeable base cations, total and particulate organic carbon, total nitrogen, C/N ratio, and earthworm density in the non-amended unfertilized natural pasture out of the experiment in 2013.

FIGURE 4 (a) Mean annual legume production in pastures and with and without Ca-amendment. (b) Mean total biomass production in the different soil uses and with and without Ca-amendment (11 years). FC, forage crop; IP, improved pasture; NA-UNP, non-amended unfertilized natural pasture out of the experiment; NP, natural pasture. Means followed by different letters indicate significant differences between treatments (LSD test, $p < .001$). Vertical bars indicate standard errors.

compared to no Ca-amendment boosted by the IP plots. At 5–15 cm, N was slightly higher in the non-amended plots due to the higher values observed in FC. After 11 years, differences by Ca-amendment disappeared and there were only differences by use: soil N followed the order $IP > NP > FC$ in 0–5 cm depth, while in 5–15 cm IP only increased N with respect to NP. In the top 5 cm of the amended plots, soil N tended to be higher in IP than in NP ($p < .1$). As for the C/N ratio, after 6 years, the Ca-amendment reduced the ratio in the 0–5 cm layer, while the two pastures showed a higher ratio than FC in 5–15 cm. After 11 years, the effect of the Ca-amendment disappeared, while NP showed significantly higher values than FC at both depths.

Neither type of use nor Ca-amendment had a significant effect on any of these variables at depth 15–30 cm, even after 11 years of application. For reference, we found mean TOC values of 20.1, 19.4 and 21.9 g kg⁻¹ for FC, NP, and IP and 19.3 and 21.6 g kg⁻¹ for amended and non-amended plots, respectively.

Compared to the non-amended unfertilized natural pasture outside the experiment, the use for 11 years of an amended and fertilized improved pasture increased TOC by 52% and 33% at the 0–5 and 5–15 cm depths,

respectively, while the amended and fertilized natural pasture achieved an increase of 39% and 23% at the 0–5 and 5–15 cm depths, respectively. Even the non-amended fertilized natural pasture achieved a remarkable increase (34% and 21%, respectively).

3.4 | Earthworm content

After 6 years, the number of earthworms per square meter in the 0–10 cm depth was not affected by the studied factors, whereas after 11 years, the content was greatly affected by the type of use, but not by the Ca-amendment (Table 5). Improved and natural pastures showed similar earthworm content (78.4 and 79.8 earthworms m⁻², respectively), which were about 4 times higher than in FC (19.6 earthworms m⁻²). The content in earthworms in the non-amended unfertilized natural pasture out of the experiment (12.6 earthworms m⁻²) was much lower than that of the fertilized natural pasture into the experiment, and even lower than in FC.

4 | DISCUSSION

4.1 | Soil chemical variables as affected by Ca-amendment and type of use

The effects of Ca-amendment on soil chemical variables such as pH, base cations and Al have been widely studied for years (e.g., Alva et al., 1986; Li et al., 2019; Shainberg et al., 1989). In our work, sugar foam waste provided Ca cations and generated OH⁻ ions, thereby neutralizing the acidity and raising the pH to at least a depth of 30 cm. As a result, Al from the soil solution precipitated in the form of insoluble hydroxides as Al(OH)₃ (Haynes & Naidu, 1998). In this way, toxic Al was completely removed in the top 15 cm and partially removed from 15 to 30 cm depth. Similar result of removing exchangeable Al in the Ap horizon (0–24 cm soil depth) with sugar foam application was described in this same soil by Peregrina et al. (2006). Additionally, it also removed the toxic forms of aluminium from the soil solution (Peregrina et al., 2007).

Magnesium was increased by the Ca-amendment thanks to the dolomite converter basic slag and the Mg sulphate added together with the sugar foam, which compensated for the Mg losses provoked by the lime amendment (Panhwar et al., 2020). This result was also found in a field experiment in the same area by Peregrina et al. (2008). Also, the K contained in the sugar foam contributed to compensate K losses.

The higher contents of Ca, Mg and K in both pastures compared to FC in the 0–5 cm soil depth could be due to

TABLE 4 Coefficient of variation of biomass production throughout 11 years of study in (a) the different soil uses and with and without Ca-amendment; (b) the non-amended unfertilized natural pasture out of the experiment.

Factor	Coefficient of variation of biomass (%)
(a)	
Soil use (SU)	
Forage crop	81.0 c
Natural pasture	67.9 b
Improved pasture	59.5 a
Ca-amendment (Ca)	
Non-amended	72.8 b
Amended	66.1 a
Effect	
SU	***
Ca	*
SUxCa	+
(b)	
Non-amended unfertilized natural pasture out of the experiment	11.1

Note: ***, *, +: $p < .001$, $p < .05$, $p < .1$, respectively in the ANOVA analysis. Means followed by different letters indicate significant differences between treatments within each factor.

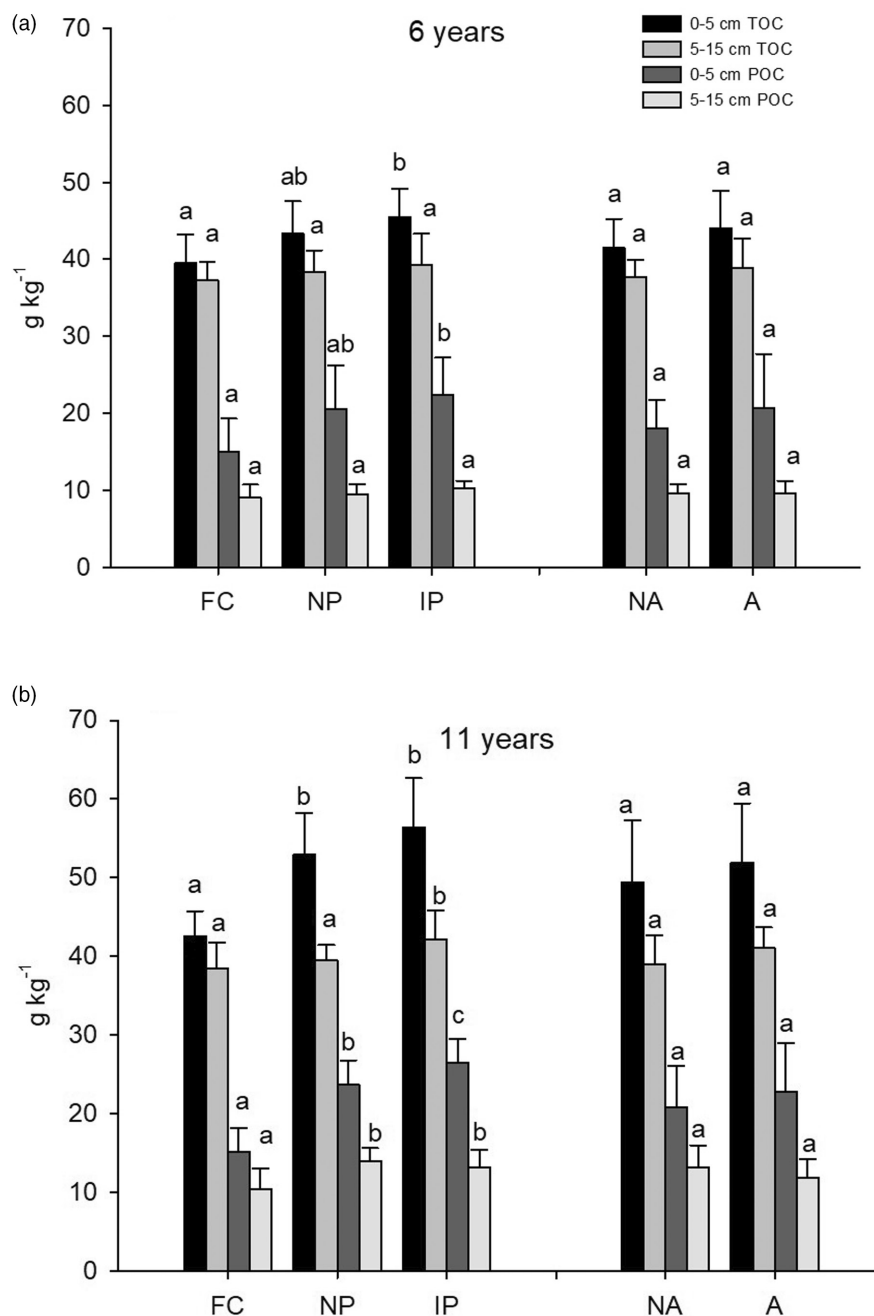


FIGURE 5 Total organic carbon (TOC), and particulate organic carbon (POC) in the different soil uses and with and without Ca-amendment after 6 (a) and 11 (b) years of their application; A, amended; FC, forage crop; IP, improved pasture; NA, non-amended; NP, natural pasture. Different letters indicate significant differences between treatments within each soil depth, (LSD test, $p < .05$).

two reasons. The first is that in both pastures, Ca and Mg (applied in autumn 2010) and K (applied annually in autumn) were not incorporated into the soil, whereas they were incorporated into soil by tillage in FC. The second reason is that the increase in TOC at the 0–5 cm depth in both pastures provides a higher effective cation exchange capacity in the soil, allowing for a greater capacity to retain base cations (Ca, Mg and K). This process of higher Ca, Mg and K content due to increased organic matter in soil surface has been described in this same raña formation when the soils were analysed across various land uses with increased degradation, from natural vegetation (cork oak forest) to a rainfed olive grove (Mariscal-Sancho et al., 2009).

Regarding the Ca-amendment effectiveness, it was similar in both FC and pasture for the whole depth despite the lack of tillage in pasture relative to FC. The high soluble carbonate content of the sugar foam (about 21% of 'active lime') contributed to facilitate its redistribution in depth with the percolation water. But also, the increase in the population of earthworms under pasture, acting as soil removers, may have promoted the redistribution of the Ca-amendment with depth, matching the effect of mechanical tillage (Lemtiri et al., 2014). Similar results regarding Ca-amendment effectiveness were found in the same area when traditional tillage versus no-tillage was compared (Hontoria et al., 2018).

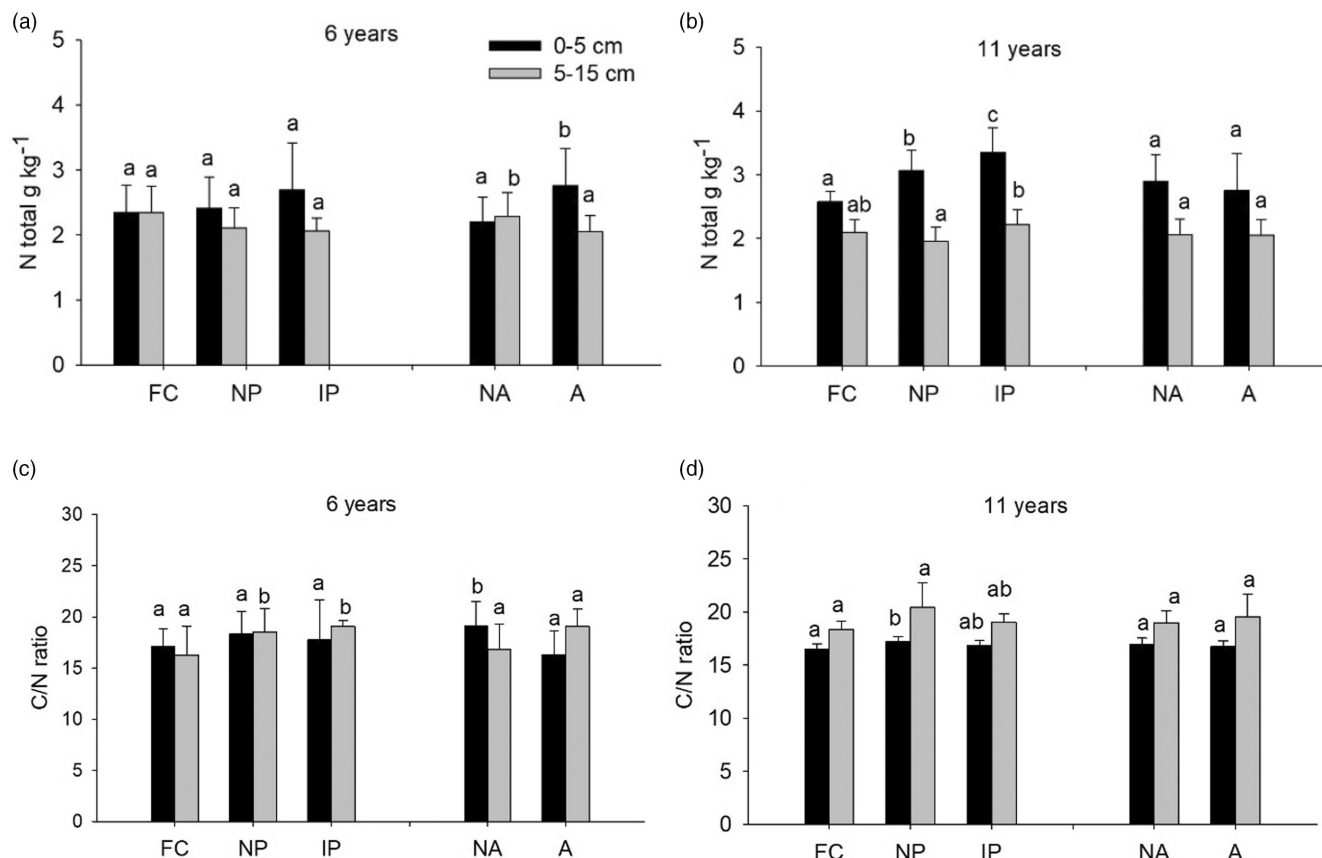


FIGURE 6 Total nitrogen after 6 (a) and 11 (b) years of application and C/N ratio after 6 (c) and 11 years (d) of application in different soil uses and with and without Ca-amendment; A, amended; FC, forage crop; IP, improved pasture; NA, non-amended; NP, natural pasture. Different letters indicate significant differences between treatments within each soil depth (LSD test, $p < .05$).

TABLE 5 Earthworm density as affected by soil use and Ca-amendment after 6 and 11 years of application.

Factor	Earthworm density (Nb. m ⁻²)	
	6 years	11 years
Soil use (SU)		
Forage crop	7.4 a	19.6 a
Natural pasture	22.2 a	79.8 b
Improved pasture	37.0 a	78.4 b
Ca-amendment (Ca)		
Non-amended	14.8 a	58.7 a
Amended	29.6 a	59.8 a
Effects		
SU	ns	***
Ca	ns	ns
SUxCa	ns	ns

Note: ns, ***: not significant and $p < .001$, respectively in the ANOVA analysis. Means followed by different letters indicate significant differences between treatments within each factor (LSD test).

In addition, Ca-amendment diminished some base cations, mainly Na until 15 cm depth, confirming the negative effect of the excess of Ca provided by the lime that promotes the lixiviation of other cations (Peregrina et al., 2006), which was also found in other field experiments in the same area (Hontoria et al., 2018; Peregrina, Mariscal, Ordóñez, et al., 2008).

4.2 | Biomass production

The biomass productions were subjected to great annual variability mainly due to the high climate variability of the Mediterranean areas (Skuras & Psaltopoulos, 2012). In all soil uses, NP, IP and FC, the highest annual biomass productions were obtained in the amended plots (Figure 4b) in line with the findings of several meta-analyses (e.g., Abdalla et al., 2022; Li et al., 2019). This was due to the Al toxicity mitigation (Cristancho et al., 2014), together with the richness of nutrients provided by the by-product-based Ca-amendment, the Mg

supplement and the increased organic matter mineralization, among others (Abdalla et al., 2022; Holland et al., 2018).

The beneficial effect of Ca-amendment on biomass was maintained over time (11 years) in contrast to other studies that reported a short-lived effect (Stevens & Laughlin, 1996) attributed to possible depletion of N reserves. In the amended plots, the legume-rich pasture (IP) tended to increase soil N to a greater extent than NP ($p < .1$) confirming the positive effect of liming on rhizobia (Andrade et al., 2002). However, the increased soil N achieved in IP (Figure 6a) did not translate into increased annual biomass production compared to NP in amended (or unamended) plots. Then, after 11 years, a legume-rich pasture did not improve the response to liming compared to a legume-poor pasture in terms of annual biomass production. The variability in the response to liming of the different pasture species (Li et al., 2019) together with weather variability may have obscured the differences between both types of pastures.

The type of use with the highest biomass production was FC (Figure 4b) due to the fertilization, tillage and seeding that this use received annually throughout the experiment. However, the biomass productions of the pastures (NP and IP) were more stable over time than those of FC (Table 4). The higher biomass production stability of pastures can be explained by the fact that in the palexerults of the Cañamero raña platform, an autumn with excessive rainfall can create a perched water table above the Bt horizon that practically reaches the soil surface, greatly affecting seed germination and crop growth (Gómez-Paccard et al., 2015). In the case of pastures, which are not tilled, a biopore space is generated by roots and earthworms, much more abundant than in the tilled plots (Table 5), whereas, in the FC plots, tillage destroys biopores every year. As a result, in the FC plots during rainy autumns, the seed germination would have been severely affected with the subsequent drop in biomass production. On the other hand, plant diversity has been related to pasture yield stability (Bonin & Tracy, 2012). In our study, plant diversity in pastures is higher than in FC, increasing growth capacity in a variety of circumstances throughout the year and leading to compensatory interactions between plants (Bai et al., 2004). Under adverse circumstances, the more competitive species are expected to compensate the least resilient to these specific limiting conditions (Wendling et al., 2019). In line with our results, Descalzi et al. (2020) found a higher growth capacity in adverse situations and less seasonality in naturalized pastures and high diversity mixtures versus two-species mixtures. Since eight new species were sown in IP plots on soil where naturalized pasture was previously growing, a higher species diversity in relation to NP would be expected, which would explain

the higher biomass stability found in IP (Table 4). In addition, with little N fertilization, the higher legume richness in IP may also have contributed to the higher biomass stability in line with the findings of Sanderson (2010).

The low total biomass and extremely low legume biomass production in the non-amended unfertilized natural pasture outside the fence relative to the fertilized NP in the experiment (Figure 4) highlights the importance of phosphate fertilization in soils with low natural fertility (Simpson et al., 2014). In line with our results, other studies in Chile (Descalzi et al., 2020; Keim et al., 2015) found that the annual biomass of unfertilized natural pasture accounted for 50–66% of different pasture management alternatives, all fertilized. This reinforces the role of fertilization in preventing soil degradation (Chaplot & Smith, 2023). In addition to fertilization, the effect of the protective fence against grazing must also be considered as a useful tool for the rehabilitation of degraded soils (Deng et al., 2014). Fencing also allowed to increase the proportion of legumes in the pasture, which were, outside the fence, preferentially consumed by livestock and wildlife (Rutter, 2006).

4.3 | Improvements in terms of organic matter parameters and earthworm content

The effect of soil use on TOC and POC was stronger than that of Ca-amendment and occurred not directly dependent on the biomass production. Thus, despite the much higher production of aerial biomass in FC plots (60% more) than in pasture plots, TOC and POC, as well as N, were higher under pastures than in the tilled FC. As tillage promotes higher mineralization of SOM (Sarker et al., 2018), a substantial part of the C from plant biomass was not ultimately retained in the soil. Compared to NP, the legume-rich pasture achieved higher values of TOC, POC and N, in most cases, earlier and deeper. The better performance of pastures, especially IP, in accumulating organic C and N can be explained by several reasons. The higher and deeper root biomass production compared to FC; thus, the aerial/root biomass ratio is 0.1–0.15 for small grain cereals, whereas in permanent pasture it is 0.65, about 5.5 times higher (Bolinder et al., 2007). Besides, roots are more effective in stabilizing C in the soil: as much as 45% of root-derived biomass can be fixed as SOM whereas only 8% of above-ground inputs are stabilized by soil (Jackson et al., 2017). Pastures provide greater protection to soil surface against the direct impact of raindrops throughout the year, whereas FC only provides protection partially in the year being absent in starting autumn when intense rains are frequent; consequently, soil aggregates are more vulnerable to break down and the organic matter is less

protected (Six et al., 2002). In another hand, pastures with legumes provide not only more N (Figure 6b) because the N biological fixation capacity, but also higher SOM accumulation (Conant et al., 2017) based in the higher biomass (above-ground and below-ground), litter biomass, as well as plant diversity (Wu et al., 2017).

In the two samplings analysed, the effect of Ca-amendment, even after new input, on TOC and POC turned out to be much smaller than the effect of use. In fact, the positive effect of Ca-amendment was only observed at 11 years and when the 15 cm depth was considered globally. This increase in TOC is explained by the higher biomass production achieved on the amended plots (Figure 4b), which implies a higher input of plant residues into the soil. Furthermore, calcium may promote SOC stabilization and may indirectly influence SOC accumulation and occlusion (Rowley et al., 2018). However, the increase in certain enzymatic activities observed in the amended plots of this trial (León et al., 2017) and in another adjacent experiment (Vazquez et al., 2017) may have favoured the mineralization of more labile organic compounds, reducing or even cancelling out the increase in TOC obtained by the increase in biomass (Abdalla et al., 2022; Paradelo et al., 2015), a loss that would be enhanced when tilled. On the other hand, the progressive increase in SOM in the unamended pasture thanks to fertilization means that the differences with the amended plots are reduced over time, weakening the effect of the Ca-amendment on these variables in the experiment. By contrast, the effect of Ca-amendment was more evident for N (Figure 6), due to the improved biological fixation of N (Li et al., 2019), although it vanished with time. Other studies in the same area showed the greater effect of the Ca-amendment on soil N relative to C and the possible decoupling between C and N mineralization (Vazquez et al., 2019).

Comparison of TOC, POC and N values with the non-amended unfertilized natural pasture outside the experiment confirms not only the adequacy of the IP composition and liming to restore soil but also the importance of fertilization (Chaplot & Smith, 2023), even if small, in this nutrient-poor soil, and certainly the protection offered by the fence against wild animals during the rehabilitation.

Tillage directly exposes earthworms to predators (such as birds) and modifies their habitats strongly (Crittenden et al., 2015; Pelosi et al., 2014). The use of rotary harrow is particularly damaging to earthworms and can be the direct cause of death of up to 64% of the worms' population (Boström, 1995), which may explain the low number of earthworms in the tilled FC plots. The anomalously low number of earthworms in the non-amended unfertilized natural pasture, outside the experimental field (Table 3), could be due, in addition to poor physico-chemical conditions (e.g., the lowest SOM in NA-UNP), to the abundance

of wild boars whose diet is sometimes based on annelid worms (Baubet et al., 2003; Massei & Genov, 2004).

5 | CONCLUSIONS

In these degraded acid soils of the Cañamero's raña surface, both improved and natural pastures, along with the application of a sugar foam waste amendment, Mg supplementation and small doses of fertilizer, significantly increased soil organic C and N in greater quantity than tilled forage crops. The legume-rich pasture proved to be better than natural pasture for increasing C and N as it achieved the increases in less time and even more depth. The unamended pasture also achieved significant increases in C and N, only slightly below the amended pasture and, in fact, the effect of the Ca-amendment on SOM parameters was not significant despite the increase in biomass production. This increase in SOM parameters has a very favourable impact on the quality of these degraded acid soils. It should not be forgotten that the degradation of the soils of Cañamero's raña began with the deforestation and cultivation of its surface, which led to rapid mineralization of organic matter and the deterioration of all the physicochemical soil properties related to it.

Both the Ca-amendment and the introduction of new legumes improved pasture biomass production and legume biomass, which notably increases the quality of natural grass. On the other hand, the use of pastures instead of forage crops means savings for the farmer in the cost of fertilizers, mainly nitrogenous, seeds and tillage. It ensures more stable biomass production over time and preserves the soil surface against rain erosion.

Pastures also enhanced the earthworm population, which is a highly biological indicator of soil quality. In the case of pastures, the earthworms help to incorporate into the soil the Ca-amendments applied on the surface. The Ca-amendment increased Ca and pH and decreased Al in all depth being the effect maximal on the 0–5 cm layer. Pastures also increased Ca, Mg, K and pH in the 0–5 cm layer.

Improving the nutritional quality of the pastures in these degraded acid soils would promote the development of extensive livestock farming and the agricultural industries associated with it, thereby positively impacting the quality of life of the population managing these resources. In short, after 11 years, we have achieved a remarkable rehabilitation of these degraded soils through sustainable land management.

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DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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