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Management Practices in Mountain Meadows: Consequences for Soil Nutrient Availability

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Abstract: Soil nutrient availability in meadows has been poorly studied from the management point of view, despite its great impact. In this study, three different types of meadows have been analysed, as follows: intensive meadows, with high livestock load and inorganic fertilization; semi-extensive meadows, with medium livestock load and organic fertilization; and extensive meadows, with low livestock load and low fertilization rates. We looked at the nitrogen, phosphorus, potassium and carbon balances of each meadow type during two different years. Nitrogen was more stable in semi-extensive and extensive meadows, due to its organic form. In contrast, intensive meadows showed higher nitrogen variability depending on climate. Phosphorus is seen as the limiting nutrient, and it accumulates less in the soil than what is estimated in the crop balance, being more balanced in extensive meadows. Potassium has a strong response to temperature, being more available in June than in February, but crop balance was always negative for extensive meadows, and its soil concentration decreases each year, which could cause long-term potassium deficiency. Carbon accumulation was more stable in extensive meadows, where there was accumulation regardless of the year, whereas intensive and semi-extensive meadows become carbon emitters during the drought year.

Keywords: grassland; nitrate; phosphorus; potassium; carbon; nutrient balance

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1. Introduction

Soil nutrient availability has been largely studied in many different crops and grasslands. It has been shown that many different factors affect it, ranging from climate to soil microorganisms. In the specific case of mountain meadows, there is not much information about nutrient availability, and even less from the management point of view [1,2].

Mountain meadows of the Spanish central Pyrenees are grazed during the spring and autumn; there is also mowing at the end of spring or the start of the summer to obtain hay for the winter [3,4]. In some cases, and depending on the climate, it is possible to have a second cut. Fertilization can vary according to location and farm management dynamics. Usually, meadows are fertilized using the manure from the farm, or they are not fertilized. We can also find meadows where inorganic fertilizers are applied to increase their productivity [5]. Typically, because of mountain orography, meadows are in small plots, with steep slopes that complicate their management. Also, their soils are usually shallow and have low fertility, with a climate that makes the growing season short, resulting in low productivity. As farms are getting larger and more mechanized, some meadows have been abandoned, and others have been intensified. In some valleys, up to 40% of meadow areas have been lost [6,7].

Meadows are composed of various species from different botanical families, making them important reservoirs of biodiversity [8]. Although plant diversity makes them more adaptable to a various range of conditions, it makes them more complex to study, as each meadow will behave differently, according to its floristic composition [9].

Management has an impact on different aspects of meadow dynamics. Mowing frequency, fertilization and livestock load can change floristic composition and nutrient availability [10,11]:

- Increasing the livestock load will increase the amount of nutrient input as excrements, but on the other hand can put excessive pressure on plants and provoke changes in meadow composition [12].
- Fertilization has been shown to be one of the major drivers of floristic composition changes, especially when there is inorganic nitrogen fertilization, which can lead to an increase in grass species and a decline in legumes [10,13,14]. Nutrient availability is also affected by changes in management. For example, when too much nitrogen is applied, it could lead to depletion of the phosphorus and potassium soil reservoir and therefore reduce yield [15,16].
- Even the fertilizer type can have an impact. Organic fertilizers are usually applied in high volumes and have much organic matter, enhancing nutrient availability and enrichment of soil, whereas inorganic fertilizers can also enrich the soil, but nutrients could remain immobilized [17,18].

The nutrient balance of meadows has been poorly analysed compared to other crops, even though it determines meadows' long-term sustainability. Nitrogen, phosphorus and potassium are the most important nutrients; if the balance becomes negative year on year, it will cause nutrient depletion and consequently yield decrease [19]. On the other hand, when the balance is positive year on year, especially in the case of nitrogen, it could lead to environmental issues like water eutrophication. In addition, a positive balance of any nutrient implies that the farmer is investing more resources than needed to get the same yield, making their business less efficient and affecting their profitability [15,20].

There are many environmental ecosystemic services that are provided by meadows, such as serving as biodiversity reservoirs, decreasing fire risks, and reducing erosion [21]. Carbon storage is also an important ecosystemic service, as meadows act as carbon sinks through the accumulation of organic matter. As there is no ploughing, organic matter accumulates in the soil, although it has been observed that during heat and drought stress, meadows can swift from carbon sinks into carbon sources during the stress [22–25].

In this study, we are going to analyse the nitrogen, phosphorus, potassium and carbon balances of three different meadow types, which have three different levels of intensification practices. Our hypothesis is that meadow intensification could increase nitrogen soil concentration, which could cause environmental problems such as water eutrophication due to nitrogen lixiviation. On the other hand, we expect phosphorus and potassium soil concentration to decrease as intensification increases, because of fertilization imbalance. We also expect to find higher carbon accumulation in extensive meadows.

2. Materials and Methods

The study is in the central area of the Spanish Pyrenees, in the valleys of the Gállego, Cinca and Ésera rivers. Along the three valleys, we sampled a total of 12 meadows corresponding to 3 different types: intensive, semi-extensive, and extensive [26,27]:

- Intensive meadows: located in the bottom of the valley, usually close to the barn, where the animals stay many days, resulting in high livestock loads. To be able to deal with the livestock load and increase their productivity, the meadows are usually fertilized with inorganic fertilizer.
- Semi-extensive meadows: located in the middle of the valley, also close to the barn and usually in deep soils with high fertility. Due to their location close to the barn, they are fertilized with manure from the farm, which increases their productivity and soil fertility. But as the climate is colder than in the bottom of the valley, there are fewer available days for grazing, resulting in lower livestock loads.
- Extensive meadows: located in the high areas of the valley and surrounded by forest, they are the fields farthest from the farm. They are rarely fertilized, mainly due to the

distance from the farm, and as a result they have lower productivity. Also, the colder climate limits the number of days where they can be grazed, which in combination with their lower productivity leads to lower livestock load capacity.

We can observe in Figure 1 that intensive meadows are in the lower parts of the valleys, and as a result they are at lower altitudes. In Table 1, we found the highest altitudes in extensive meadows. All meadows except extensive meadows are fertilized yearly. The fertilizer type is organic, except in intensive meadows, where it is inorganic. Slopes are higher in semi-extensive and extensive meadows. Legume cover is similar in all cases, being more variable in intensive meadows. All meadows are in Haplic Regosol soils. Intensive meadows have more clay content, whereas extensive meadows have more sand. pH is higher in intensive meadows. Conductivity is higher in semi-extensive meadows. Organic matter in extensive and semi-extensive meadows is more than double that of intensive meadows.

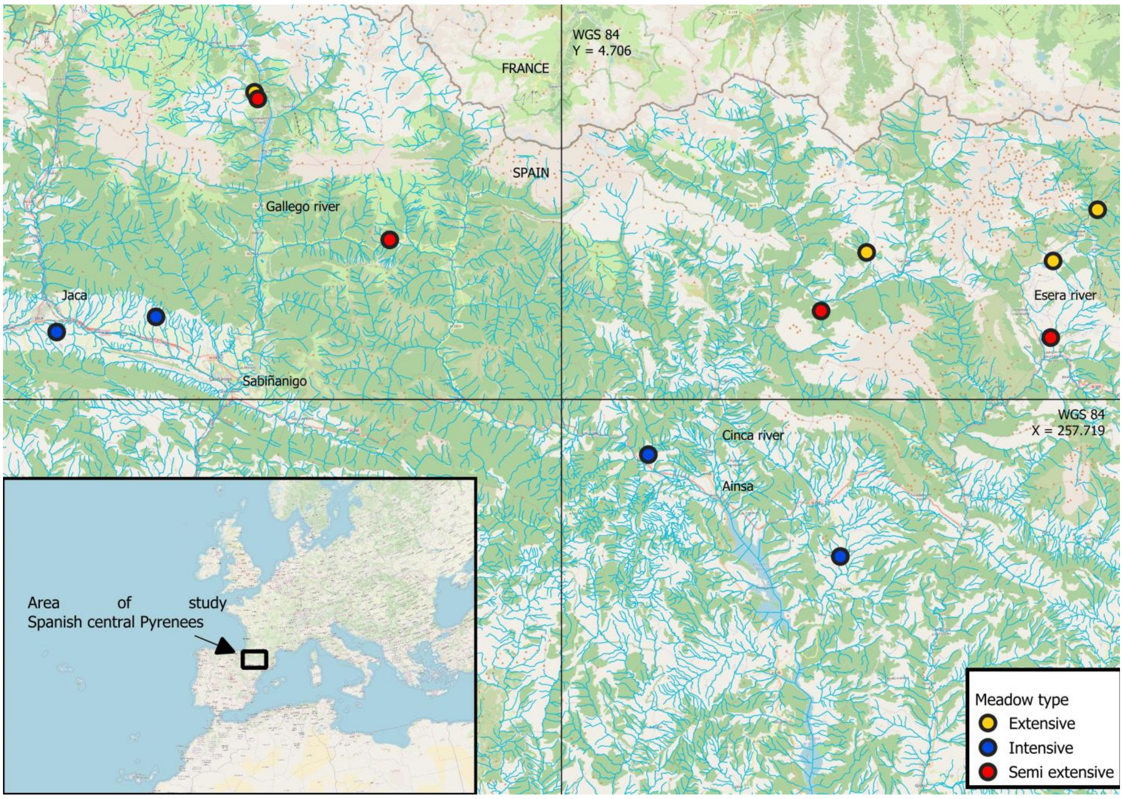

Figure 1. Map of studied meadows.

Table 1. Meadow characteristics [3].

	Intensive Meadow	Semi-Extensive Meadow	Extensive Meadow
Altitude (m)	602–890	902–1290	1100–1612
Fertilization type	Inorganic	Organic	Organic/None
Fertilization frequency	Yearly	Yearly	Rarely
Slope (%)	9.63 ± 4.13	18.6 ± 4.99	16.1 ± 5.35
Legume cover (%)	26.25 ± 21.99	24.3 ± 5.95	23.3 ± 5.33
Soil type (WRB)	Haplic Regosol	Haplic Phaeozem	Haplic Phaeozem
Clay (%)	30.47 ± 4.87	23.62 ± 4.26	16.29 ± 5.04
Sand (%)	21.01 ± 7.92	40.50 ± 9.49	51.61 ± 9.88
pH	7.71 ± 0.3	6.94 ± 0.29	6.82 ± 0.41
Electric conductivity (dS/m)	0.23 ± 0.05	0.28 ± 0.06	0.21 ± 0.06
Organic matter (%)	3.78 ± 2.12	9.93 ± 3.58	9.25 ± 3.18

Hay samples were taken from 6 plot enclosures (40 cm × 60 cm), half of them being mowed as the same time as the farmer and the other half earlier, when the crop reached its optimal protein content. Production (kg DM/ha) was calculated by weighing the oven-dried biomass (65 °C for 48 h).

For nutrient extraction, protein and fibre content, samples were taken to the laboratory, where the determinations were performed as follows: laboratory dry matter at 105 °C for 4 h; nitrogen content (N) was determined using the Kjeldahl method, and crude protein (CP) concentrations were calculated from it by multiplying N × 6.25. Ash-free neutral detergent fibre (NDF) and acid detergent fibre (ADF) were quantified using an Ankom 200 fibre analyser (Ankom Technol. Corp., Fairport, NY, USA), according to Van Soest et al. [28].

Relative feed value (RFV) is an index that combines important nutritional factors (potential intake and digestibility) into a single number, providing a quick and effective method for evaluating feed value or quality. The RFV was calculated using the estimates of digestible dry matter (DDM%) and potential dry matter intake (DMI% of body weight) of the forage, based on the ADF and the NDF fractions [29].

Soil samples of 1 kg were taken at random from 3 different places in the meadows using an Eijkelkamp hand auger and homogenized into a single sample. They were taken at two times: at the beginning of the year, during February, before fertilizer was applied, and the last one in June, right after hay harvest.

Soil analysis covered nitrogen in its nitrate fraction by spectrophotometry analysis, phosphorus by the Olsen method, potassium by ammonic acetate extraction, and organic matter by spectrophotometry.

The Braun-Blanquet method [30] was used to carried out flora inventories in the central 100 m^2 of each meadow. From them, the Shannon index was used to calculate plant biodiversity (35).

The climatic parameters were obtained from the climatic stations 9446, 9789A, 9784P, 9814X, 9838A, 9838B, and 9843A of the network of the Agencia Estatal de Meteorología [31]. The accumulated rainfall and the accumulated evapotranspiration (ETO) were calculated daily from March 1st using the Penman-Monteith method. Evapotranspiration was calculated from temperature data according to CROPWAT 8.0 procedures [32]. The growing degree days were calculated 1 February 1st by the sum of the daily average temperatures when they were between 0 and 18 °C. If the averages were negative, we limited them to 0 °C, and to 18 °C when they were > 18 °C [33,34]. All climate parameters were calculated until the mowing day.

Farm information was obtained from interviews with the farmers where they were asked how much time the meadow is grazed, the number of animals, how much fertilizer is applied and what type, and what is the average production of the meadow. Stocking rate was expressed as livestock units (LU) per ha.

As was shown in [27], spring grazing corresponds to 15% of the hay production, whereas autumn grazing is 25% of the hay production. In order to get the nutrient extraction by grazing, we use the following equation:

$$G = (K_a \cdot 0.25 \cdot M) + (K_s \cdot 0.15 \cdot M) \quad (1)$$

where G is nutrient extraction by grazing, M is nutrient extraction by mowing, K_a is a coefficient that indicates if the meadow was grazed in autumn (1 if grazed, 0 if not) and K_s is a coefficient that indicates if the meadow was grazed in spring (1 if grazed, 0 if not).

Nutrient input via excrements were estimated using stocking load, and data from previous studies were nutrient concentrations of livestock excrements were determined [35], as shown in the following equation:

$$E = N \cdot C \quad (2)$$

where E is nutrient input by excrements, N is the number of days spent by the animal in the meadow per hectare, and C is the daily nutrient input according to the literature, as it can be summarized in Table 2:

Table 2. Estimation of nutrient content in excrements [35].

	N (kg day^{-1})	P (kg day^{-1})	K (kg day^{-1})
Cow	0.2192	0.0767	0.2685
Sheep	0.0246	0.0086	0.0302

Nitrogen fixation was estimated according to meadow legume cover and using data from previous studies, which calculated 160 kg ha^{-1} for Pyrenees meadow legumes [27]. The following equation was used:

$$NX = 160 \cdot LC \tag{3}$$

where NX is nitrogen fixation by legumes in kg ha^{-1}, and LC is legume cover in m^2 of legume surface per m^{-2} of crop surface.

Nutrient crop balance was calculated by adding the values of nitrogen fertilization and nitrogen content estimated in animal droppings and subtracting nutrient extraction by mowing and estimated nutrient extraction by grazing, as shown in the following equations:

$$NB = NF + NE + NX - NM - NG \tag{4}$$

where NB is nitrogen balance, NF is nitrogen fertilization, NE is nitrogen in excrements, NX is nitrogen fixation, NE is nitrogen extracted by mowing, and NG is nitrogen extracted by grazing.

$$PB = PF + PE - PM - PG \tag{5}$$

where PB is phosphorus balance, PF is phosphorus fertilization, PE is phosphorus in excrements, PM is phosphorus extracted by mowing, and PG is phosphorus extracted by grazing.

$$KB = KF + KE - KM - KG \tag{6}$$

where KB is potassium balance, KF is potassium fertilization, KE is potassium in excrements, KM is potassium extracted by mowing, and KG is potassium extracted by grazing.

Soil organic carbon (SOC) was calculated using the following formula:

$$SOC\left[Mg\ ha^{-1}\right] = OC \cdot LT \cdot BD \cdot (1 - RF) \cdot 10^4 \tag{7}$$

where OC is the organic concentration (%), LT is the layer thickness (in our case 0.3 m), BD is the bulk density (Mg m^{-3}), and RF is the rock fragment concentration [36].

To calculate soil balance, nutrient soil concentration in June was subtracted by nutrient concentration in February, as shown in the following equation:

$$SB = N_j - N_f \tag{8}$$

where SB is soil nutrient balance, N_j is soil nutrient content in June, and N_f is soil nutrient content in February.

All data were checked by the Shapiro–Wilk normality test, and as the data were nonparametric, the Wilcoxon test was used to compare differences among meadow type and year. Additionally, the post hoc Wilcoxon test was carried out to check between which group were the differences.

We have considered the differences to be statistically significant when $p < 0.05$. All statistical analyses were carried out using R version 4.4.0 [37].

3. Results

3.1. General Characterization

The following table shows the general parameters of the farms during each year of study.

As shown in Table 3, intensive meadows had the lowest Shannon Index, whereas extensive meadows had the highest. On the other hand, livestock load had the opposite effect pattern, being higher in intensive meadows and the lowest in extensive meadows. Looking at climate variables, extensive and semi-extensive meadows had similar precipitation and evapotranspiration, being significantly higher than in intensive meadows. Degree days showed no significant difference between each meadow type.

Table 3. General parameters of 2022. Shannon biodiversity index, stocking rate expressed in livestock units per hectare, production expressed in kilograms of dry matter per hectare, precipitation expressed in millimetres of rainfall from March 1st to mowing date, degree days from February 1st to mowing date expressed in degrees Celsius, evapotranspiration (ETO) expressed in millimetres from March 1st to mowing date, crude protein (CP) expressed in percentage from dry matter and relative feed value (RFV). Mean and standard deviation. Sig: significance differences for $p < 0.05$; different letters in the same row indicate differences (Wilcoxon test).

	Intensive Meadow	Semi-Extensive Meadow	Extensive Meadow
Shannon index	1.79 ± 0.18^{c}	2.84 ± 0.31^{b}	3.23 ± 0.14^{a}
Stocking rate (LU/ha)	0.56 ± 0.08^{a}	0.33 ± 0.29^{b}	0.20 ± 0.10^{c}
Production (kgDM/ha)	6097.23 ± 1367.54^{a}	5273.94 ± 1583.28^{a}	3544.45 ± 915.09^{b}
Precipitation (mm)	193.05 ± 29.35^{b}	345.53 ± 64.75^{a}	322.05 ± 54.74^{a}
Degree days (°C)	1182.99 ± 67.38^{a}	1227.19 ± 259.81^{a}	1022.17 ± 235.97^{a}
ETO (mm)	310.28 ± 8.95^{b}	366.28 ± 69.84^{a}	357.69 ± 37.91^{a}
CP (% DM)	10.01 ± 2.24^{a}	11.71 ± 3.65^{a}	11.56 ± 2.19^{a}
RFV	100.97 ± 7.31^{b}	114.24 ± 23.51^{ab}	119.83 ± 16.72^{a}

There were no significant differences in protein content, but RFV was higher in extensive meadows and lower in intensive meadows.

Table 4 shows fewer differences than Table 3. Although we can find significant differences in biodiversity from each meadow type, we cannot find significant differences in livestock load between extensive and semi-extensive meadows.

Table 4. General parameters of 2023. Shannon biodiversity index, stocking rate expressed in livestock units per hectare, production expressed in kilograms of dry matter per hectare, precipitation expressed in millimetres of rainfall from March 1st to mowing date, degree days from February 1st to mowing date expressed in degrees Celsius, evapotranspiration (ETO) expressed in millimetres from March 1st to mowing date, crude protein (CP) expressed in percentage from dry matter and relative feed value (RFV). Mean and standard deviation. Sig: significance differences for $p < 0.05$; different letters in the same row indicate differences (Wilcoxon test).

	Intensive Meadow	Semi-Extensive Meadow	Extensive Meadow
Shannon index	1.82 ± 0.15^{c}	2.76 ± 0.33^{b}	3.23 ± 0.14^{a}
Stocking rate (LU/ha)	0.59 ± 0.10^{a}	0.16 ± 0.04^{b}	0.20 ± 0.10^{b}
Production (kgDM/ha)	2329.28 ± 1332.86^{b}	3665.58 ± 1207.28^{a}	2443.73 ± 1285.41^{ab}
Precipitation (mm)	180.40 ± 44.79^{b}	289.97 ± 83.85^{a}	298.40 ± 128.66^{a}
Degree days (°C)	1142.18 ± 185.32^{a}	1084.02 ± 270.86^{ab}	919.66 ± 286.82^{b}
ETO (mm)	320.15 ± 38.26^{a}	331.27 ± 61.98^{a}	337.06 ± 81.73^{a}
CP (% DM)	14.56 ± 4.98^{a}	13.09 ± 2.10^{a}	14.56 ± 3.08^{a}
RFV	111.04 ± 16.38^{b}	124.66 ± 15.20^{a}	147.11 ± 56.59^{a}

In Table 5 we observed that production showed fewer differences than in the previous year and they were considerably lower. Precipitation was also lower in 2023 than in 2022, but it showed the same tendency, being higher in semi-extensive and extensive meadows.

Differences in degree days showed a similar pattern, being higher in extensive meadows and lower in intensive meadows. On the other hand, evapotranspiration showed no significant differences.

Table 5. General parameters comparison between 2022 and 2023. Production expressed in kilograms of dry matter per hectare, precipitation expressed in millimetres of rainfall from March 1st to mowing date, degree days from February 1st to mowing date expressed in degrees Celsius, evapotranspiration (ETO) expressed in millimetres from March 1st to mowing date, crude protein (CP) expressed in percentage from dry matter and relative feed value (RFV). Mean and standard deviation. Sig: significance differences for $p < 0.05$; different letters in the same row indicate differences (Wilcoxon test).

	2022	2023
Production (kgDM/ha)	4746.80 + 1663.08 ^{a}	2735.34 + 1404.00 ^{b}
Precipitation (mm)	305.64 + 79.54 ^{a}	253.19 + 108.19 ^{b}
Degree days (°C)	1136.34 + 243.17 ^{a}	1045.40 + 268.28 ^{a}
ETO (mm)	351.64 + 54.63 ^{a}	329.33 + 63.74 ^{b}
CP (% DM)	11.31 + 2.94 ^{b}	14.16 + 3.75 ^{a}
RFV	113.82 + 19.78 ^{b}	127.87 + 39.56 ^{a}

In contrast with the previous year, we found significant differences in protein content, it being higher in intensive and extensive meadows than in semi-extensive meadows. RFV also had the same behaviour.

As shown in Figure 2, temperature had similar patterns in both years, the climate being warmer in 2022 than 2023, whereas spring was warmer in 2023 than 2022. It should be noted that those higher temperatures in spring matched lower rainfall in March and April, a critical period for meadow growth. Indeed, this drought period lasted until the end of May, when there began to appear heavy rains. In contrast, autumn showed huge rainfall in 2023, when there were flooding events.

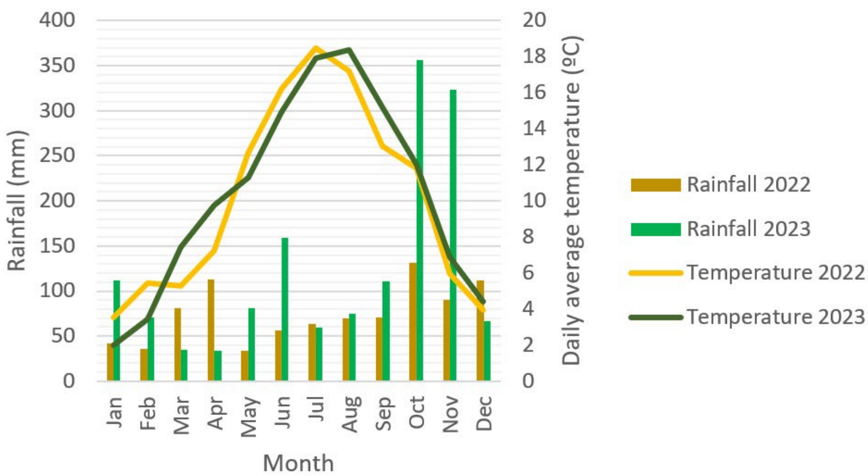

Figure 2. Average daily temperature and monthly rainfall in 2022 and 2023.

3.2. Nitrogen

Crop balance and soil balance in nitrogen during each year:

In both cases (Tables 6 and 7), there are significant differences in nitrogen fertilization for each meadow type. There are fewer differences in grazing, excrements, fixation and mowing. Crop balances are significantly different for each meadow type, and soil balance has no significant differences between semi-extensive and extensive meadows.

Table 6. Nitrogen balance of 2022 expressed in kg NO_3^- ha^{-1}. Mean and standard deviation. Sig: significance differences for $p < 0.05$; different letters in the same row indicate differences (Wilcoxon test).

		Intensive Meadow	Semi-Extensive Meadow	Extensive Meadow
Input	Fertilization	58.20 ± 44.20 ^{b}	219.22 ± 131.30 ^{a}	6.17 ± 10.69 ^{c}
	Excrements	55.13 ± 7.49 ^{a}	26.06 ± 17.24 ^{b}	19.70 ± 9.25 ^{b}
	Fixation	64.02 ± 45.78 ^{a}	38.88 ± 10.65 ^{a}	37.32 ± 9.54 ^{a}
Output	Mowing	96.39 ± 27.99 ^{a}	92.83 ± 25.28 ^{a}	66.02 ± 22.32 ^{b}
	Grazing	24.10 ± 7.00 ^{a}	25.98 ± 6.18 ^{a}	19.93 ± 10.79 ^{a}
	Crop balance	56.88 ± 33.40 ^{b}	165.35 ± 106.36 ^{a}	−22.76 ± 31.41 ^{c}
Soil	February	62.40 ± 3.90 ^{c}	195.00 ± 94.37 ^{a}	83.17 ± 26.70 ^{b}
	June	62.40 ± 35.10 ^{c}	341.25 ± 203.67 ^{a}	208.65 ± 149.13 ^{b}
	Soil balance	0.00 ± 31.20 ^{a}	146.25 ± 225.64 ^{b}	125.48 ± 131.26 ^{b}

Table 7. Nitrogen balance of 2023 expressed in kg NO_3^- ha^{-1}. Mean and standard deviation. Sig: significance differences for $p < 0.05$; different letters in the same row indicate differences (Wilcoxon test).

		Intensive Meadow	Semi-Extensive Meadow	Extensive Meadow
Input	Fertilization	67.16 ± 37.45 ^{b}	251.90 ± 136.80 ^{a}	6.17 ± 10.69 ^{c}
	Excrements	54.77 ± 7.70 ^{a}	16.33 ± 4.22 ^{b}	19.70 ± 9.25 ^{b}
	Fixation	41.99 ± 39.34 ^{a}	40.41 ± 11.91 ^{a}	37.32 ± 9.54 ^{a}
Output	Mowing	47.24 ± 21.08 ^{b}	75.49 ± 26.11 ^{a}	53.14 ± 23.24 ^{b}
	Grazing	11.81 ± 5.27 ^{b}	18.87 ± 6.53 ^{a}	15.92 ± 9.92 ^{ab}
	Crop balance	104.88 ± 17.79 ^{b}	214.29 ± 123.08 ^{a}	−5.87 ± 32.33 ^{c}
Soil	February	29.25 ± 19.60 ^{b}	93.60 ± 40.65 ^{a}	31.20 ± 19.69 ^{b}
	June	246.68 ± 73.14 ^{c}	390.00 ± 0.00 ^{a}	288.60 ± 145.82 ^{b}
	Soil balance	217.42 ± 58.98 ^{a}	296.40 ± 40.65 ^{b}	257.40 ± 132.05 ^{b}

3.3. Phosphorous

Crop balance and soil balance in phosphorous during each year.

As was shown in the case of nitrogen, phosphorus shows the same differences in fertilization and in grazing and excrements. However, in mowing we found more significant differences in the year 2022 (Table 8) than in 2023 (Table 9).

Table 8. Phosphorous balance of 2022 expressed in kg $P_2O_5^{2-}$ ha^{-1}. Mean and standard deviation. Sig: significance differences for $p < 0.05$; different letters in the same row indicate differences (Wilcoxon test).

		Intensive Meadow	Semi-Extensive Meadow	Extensive Meadow
Input	Fertilization	37.82 ± 15.42 ^{b}	309.30 ± 275.90 ^{a}	11.57 ± 20.05 ^{c}
	Excrements	19.29 ± 2.62 ^{a}	9.12 ± 6.03 ^{b}	6.89 ± 3.24 ^{b}
Output	Mowing	31.38 ± 7.86 ^{a}	25.99 ± 10.92 ^{b}	15.50 ± 7.02 ^{c}
	Grazing	7.84 ± 1.97 ^{a}	7.37 ± 3.02 ^{a}	4.54 ± 2.37 ^{b}
	Crop balance	17.90 ± 13.77 ^{b}	285.05 ± 264.68 ^{a}	−1.58 ± 14.11 ^{c}
Soil	February	540.33 ± 477.81 ^{a}	468.88 ± 423.85 ^{a}	122.80 ± 51.45 ^{a}
	June	611.77 ± 486.74 ^{a}	482.27 ± 502.01 ^{a}	109.40 ± 44.38 ^{b}
	Soil balance	71.45 ± 8.93 ^{a}	13.40 ± 211.39 ^{a}	−13.40 ± 34.30 ^{b}

Table 9. Phosphorous balance of 2023 expressed in kg $P_2O_5{}^{2-}$ ha^{-1}. Mean and standard deviation. Sig: significance differences for $p < 0.05$; different letters in the same row indicate differences (Wilcoxon test).

		Intensive Meadow	Semi-Extensive Meadow	Extensive Meadow
Input	Fertilization	47.48 ± 14.83 ^{b}	365.52 ± 298.08 ^{a}	11.57 ± 20.05 ^{c}
	Excrements	19.17 ± 2.69 ^{a}	5.72 ± 1.48 ^{b}	6.89 ± 3.24 ^{b}
Output	Mowing	12.19 ± 6.19 ^{b}	18.60 ± 8.75 ^{a}	11.91 ± 8.64 ^{b}
	Grazing	3.05 ± 1.55 ^{b}	4.65 ± 2.19 ^{a}	3.45 ± 2.54 ^{ab}
	Crop balance	51.41 ± 19.10 ^{b}	347.98 ± 293.41 ^{a}	3.11 ± 15.00 ^{c}
Soil	February	551.49 ± 785.76 ^{a}	628.15 ± 664.24 ^{a}	229.97 ± 200.44 ^{a}
	June	424.22 ± 401.67 ^{ab}	503.11 ± 461.73 ^{a}	174.15 ± 128.26 ^{b}
	Soil balance	−127.27 ± 410.02 ^{a}	−125.03 ± 202.61 ^{a}	−55.82 ± 85.52 ^{a}

Crop balance had significant differences between each meadow type in both years, but soil balance lacks significant differences; only in 2022 was phosphorus soil balance significantly lower in extensive meadows.

Even though crop and soil balance are notoriously different in every case, in year 2022 (Table 8) they have the same tendency. In year 2023 (Table 9), they had the opposite tendency.

3.4. Potassium

Crop balance and soil balance in potassium during each year:

Fertilization, grazing, and excrements show the same differences as in the case of nitrogen and phosphorus. Mowing is lower in extensive meadows, but in 2023 was like that in intensive meadows.

Crop balance is similar in 2022 (Table 10), but it was significantly lower in extensive meadows in 2023 (Table 11). In soil balance, we find differences in 2022 (Table 10), but in 2023 (Table 11) the differences were less significant.

Table 10. Potassium balance of 2022 expressed in kg K_2O ha^{-1}. Mean and standard deviation. Sig: significance differences for $p < 0.05$; different letters in the same row indicate differences (Wilcoxon test).

		Intensive Meadow	Semi-Extensive Meadow	Extensive Meadow
Input	Fertilization	79.20 ± 23.20 ^{a}	143.32 ± 142.46 ^{a}	11.57 ± 20.05 ^{b}
	Excrements	67.54 ± 9.17 ^{a}	31.92 ± 21.11 ^{b}	24.13 ± 11.33 ^{b}
Output	Mowing	167.77 ± 27.27 ^{a}	155.23 ± 71.52 ^{a}	74.42 ± 27.79 ^{b}
	Grazing	41.94 ± 6.82 ^{b}	43.80 ± 18.80 ^{a}	22.52 ± 13.03 ^{c}
	Crop balance	−62.97 ± 41.37 ^{a}	−23.79 ± 79.66 ^{a}	−61.24 ± 36.85 ^{a}
Soil	February	2676.96 ± 1890.72 ^{a}	1701.18 ± 1538.35 ^{b}	844.74 ± 406.94 ^{b}
	June	6144.84 ± 4984.20 ^{a}	2098.98 ± 1662.64 ^{b}	1067.04 ± 640.94 ^{b}
	Soil balance	3467.88 ± 3093.48 ^{a}	397.80 ± 246.36 ^{b}	222.30 ± 850.10 ^{c}

Table 11. Potassium balance of 2023 expressed in kg K_2O ha^{-1}. Mean and standard deviation. Sig: significance differences for $p < 0.05$; different letters in the same row indicate differences (Wilcoxon test).

		Intensive Meadow	Semi-Extensive Meadow	Extensive Meadow
Input	Fertilization	69.56 ± 35.56 [a]	166.20 ± 158.00 [a]	11.57 ± 20.05 [b]
	Excrements	67.09 ± 9.43 [a]	20.01 ± 5.17 [b]	24.13 ± 11.33 [b]
Output	Mowing	53.66 ± 28.62 [b]	94.60 ± 42.24 [a]	57.65 ± 32.15 [b]
	Grazing	13.41 ± 7.15 [b]	23.65 ± 10.56 [a]	17.45 ± 12.71 [b]
	Crop balance	69.58 ± 36.03 [a]	67.96 ± 140.52 [a]	−39.40 ± 41.14 [b]
Soil	February	2024.10 ± 2150.68 [a]	2165.28 ± 1605.97 [a]	788.58 ± 530.16 [b]
	June	2665.26 ± 3084.64 [a]	2458.56 ± 1714.44 [a]	835.38 ± 347.48 [b]
	Soil balance	641.16 ± 943.33 [a]	293.28 ± 115.99 [a]	46.80 ± 307.24 [b]

3.5. Carbon

Soil balance in carbon during each year (Table 12):

Table 12. Carbon balance of 2022 and 2023 in Mg SOC ha^{-1}. Mean and standard deviation. Sig: significance differences for $p < 0.05$; different letters in the same row indicate differences (Wilcoxon test).

		Intensive Meadow	Semi-Extensive Meadow	Extensive Meadow
2022	February	73.52 ± 20.13 [b]	192.85 ± 53.17 [a]	222.49 ± 59.27 [a]
	June	86.64 ± 23.30 [b]	225.65 ± 47.44 [a]	225.99 ± 44.56 [a]
	Soil balance	13.12 ± 3.17 [a]	32.80 ± 58.44 [a]	3.51 ± 51.46 [a]
2023	February	91.73 ± 56.04 [b]	267.09 ± 91.65 [a]	196.24 ± 80.85 [a]
	June	79.52 ± 25.26 [b]	214.38 ± 8.06 [a]	224.07 ± 28.60 [a]
	Soil balance	−12.22 ± 35.19 [a]	−52.71 ± 84.13 [a]	27.82 ± 79.99 [a]

Intensive meadows have lower carbon content than semi-extensive and extensive meadows. Carbon balance was always positive in year 2022, but in 2023 it was positive only in extensive meadows.

4. Discussion

We analyze the results according to type and year.

4.1. Year Variability

This study was carried out in two years with different climate behaviour. If we look just at the global numbers, we see not many differences, but if we look at precipitation distribution, those differences appear to be clear. Looking at Figure 2, we can observe that in 2023 there was less precipitation from March to the end of May, a critical period in crop development, and temperatures were higher, causing drought stress in may crops. In the lowest parts of the valley, where the cycle is faster, the plants started flowering at low height and yielded markedly low yields. Indeed, due to the spring drought, the local government had to implement special aid to the farmers to help them to buy feed for their animals, because there was very little pasture available [38]. The same pattern has been observed in other studies [8].

As was shown in other papers, when yield falls, quality, in terms of protein and RFV, rises [3,12]. Consequently, in 2023 we found higher protein and RFV values than in 2022.

It is quite interesting to note that extensive meadows showed the lowest yield fall in the drought year (2023). It has been shown that a higher diversity index is correlated with lower yields, but also with higher resilience to stresses [21,39].

Looking at nitrogen, we found higher nitrogen extractions in 2022 than in 2023, due to its higher yield, similar to other cases [40]. Crop balance was positive in semi-extensive and intensive meadows both years, whereas in extensive meadows a negative balance occurred in both years. Considering that extensive meadows had almost no nitrogen applied in fertilization, this seems like a logical consequence. In 2023, we had higher nitrogen accumulation in the crop balance, due to lower production with similar fertilization. In order to simplify calculations, we have considered nitrogen fixation as a constant, regardless of climate, but considering drought stress during 2023 that limited legume development, nitrogen fixation could be lower than what we have considered, as has been shown in other studies [41,42].

Crop balance and soil balance differ from each other in most cases. Those differences are higher in 2023, most likely being due to climate. Looking at February soil nitrogen content in Tables 6 and 7, we observe that 2023 had half of the nitrogen soil content of 2022, and if we look at Figure 2, winter temperatures were lower in 2023. On the other hand, nitrogen soil content in June was higher in 2023 than in 2022, and spring temperatures contrasted with winter temperatures, being higher in 2023 than in 2022. Some studies have shown that temperature can alter nitrogen soil content [43,44], which could be one of the driving factors that lead to differences between crop and soil balance.

In phosphorus, we also had higher extraction in mowing in 2022 than in 2023, due to the higher yield. Crop balance was always positive except for extensive meadows in 2022, which had a small phosphorus deficit, caused by the higher yield this year and the same fertilization. Soil balance was positive in 2022 for intensive and semi-extensive meadows, whereas in extensive meadows and all meadows in 2023 it was negative. That is especially noted in intensive meadows, where the crop balance indicates phosphorus accumulation and soil balance shows phosphorus deficit; it has been shown that, in some meadows, phosphorus is most limiting nutrient [19,45]. As phosphorus availability is highly dependent on microbial dynamics, drought conditions and higher temperatures during the spring could have led to higher phosphorus blockage, as well as increasing phosphorus intake by the plant due to the increasing temperatures [46].

As was the case for nitrogen and phosphorus, potassium also had higher extraction values in mowing in 2022 due to the higher yield. Caused by the higher yield, 2022 showed a potassium deficit in every meadow type, in contrast to 2023 where only extensive meadows had a potassium deficit. Other studies have seen potassium deficits in meadows [5]. However, the soil balance was positive in both years for all meadow types. Indeed, it was higher in 2022 when the potassium crop balance was lower; in some cases, potassium accumulation has been related to lower-than-average yields [47].

Carbon balance varied by year and meadow type. In 2022, there was carbon accumulation, when meadows acted as carbon sinks. In contrast, in 2023 only extensive meadows had positive carbon balances, making semi-extensive and intensive meadows carbon emitters during that year. It has been shown that, in drought conditions, the carbon balance can be negative in meadows [23,48].

4.2. Meadow Type

As intensification increases, by increasing livestock load and fertilization, biodiversity decreases, as has been reflected in many papers [49]. Semi-extensive meadows had the higher fertilization rate, but given its organic nature, it had a lower impact in biodiversity than the inorganic fertilizers used in intensive meadows. It should be noted that intensive meadows are considered by farmers as the least productive fields, as they also have fields with higher production with cereals and forage crops such as alfalfa, where they use their manure. In semi-extensive meadows, however, due to their higher slopes and smaller plots, cereals and forage crops are rarely grown, so all the manure is applied on them.

Precipitation varies according to meadow location. Intensive meadows' locations in the bottoms of the valleys explain why they have lower precipitation, which increases by around 100 mm of rainfall for each 100 m of altitude gain [50]. Water losses due to runoff are small, thanks to terracing that reduces slopes [51]. On the other hand, degree days have been identified as one of the major drivers in meadow development; when the meadow reaches 900 °C, it starts flowering; then, depending on climate, the farmer will mow, leading to differences depending on when the weather is favourable to mowing.

From the quality point of view, protein content does not depend on meadow type but is mostly driven by yield. As yield increases, protein content decreases [3,12]. On the other hand, RFV increases as biodiversity increases, although yield seems to have a similar effect, as was seen in protein content.

Nitrogen inputs are higher in semi-extensive meadows, because of the use of manure from the farms. Some of the nitrogen will not be available to the crop, as it will be used by microbes to degrade organic matter. Also, the nitrogen in manure is more stable than in inorganic fertilizer, which can have more losses in lixiviation [52].

Intensive and semi-extensive meadows had the highest nitrogen extraction values in mowing in 2022, whereas in 2023 semi-extensive meadows had the highest values. Probably, increasing nitrogen availability increases nitrogen extraction by the plant, which will be coherent with other studies [1,53].

Extensive meadows always show a nitrogen deficit in crops; since no fertilizer is applied, that result is logical. In the soil balance, semi-extensive meadows have fewer differences between crop and soil balance. In both years, semi-extensive and extensive meadows had the highest nitrogen accumulation, proving that inorganic fertilization could have poorer results than organic or no fertilization in meadows. Organic fertilization has more complex dynamics, which leads to bigger changes during the year, but if we compare nitrogen soil content in the same period of both years, we find that nitrogen content increases [20]. Intensive meadows have the lowest deficits in both years, as most of the nitrogen is applied by inorganic fertilizer, and most of the nitrogen that is not consumed by the plant is lixiviated [1,54].

There are clear differences in the phosphorus crop balance between each meadow type, the lowest being in the extensive meadows, where they are close to being balanced. On the other hand, semi-extensive meadows show the highest phosphorus accumulation in the crop balance. Nonetheless, both intensive and semi-extensive meadows show lower soil phosphorus accumulation than in the crop balance; when phosphorus is limited, it could cause a decrease in legumes, which could explain the lower Shannon index [55]. In both cases, fertilization could have led to an increase in blocked phosphorus, which was higher in the drought year. In contrast, extensive meadows show lower differences, as no fertilizer was applied. The absence of fertilization has been related to higher soil biological dynamics, which could lead to the higher stability of phosphorus that we have observed in extensive meadows [56,57]. Soil phosphorus balance in intensive meadows had the opposite trend, showing the biggest variability between each year. As inorganic fertilization has a negative effect in soil biological dynamics, there is a greater variation in phosphorus soil accumulation [58].

Potassium seems to have a different behaviour from nitrogen and phosphorus. Extensive meadows had potassium deficit both years, while intensive and semi-extensive meadows showed a deficit in 2022, the year with higher production, and accumulation in 2023, when yield was lower. Those results were expected according to their circumstances, but in soil, regardless of the crop balance trend, in all cases there is potassium accumulation. Temperature could be the biggest driver of this phenomena, as has been shown in many papers; as temperature decreases, potassium availability also decreases [54,59–61]. As soil balance is calculated as the difference between potassium content in June minus potassium content in February, there are important temperature differences between both sample dates [62,63]. In any case, it seems difficult to find potassium deficiency in meadows; it could only appear in high-yielding meadows with low potassium fertilization [64].

Intensification has been correlated with lower carbon storage, by increasing cut frequency or by increasing fertilization [65]. However, as shown in Table 12, although intensive meadows have significantly lower SOC, extensive and semi-extensive meadows have no significant differences, which leads us to argue that some degree of meadow intensification can be achieved without decreasing SOC. Meadows have remarkable carbon storage capacity, especially semi-extensive and extensive meadows, where we found carbon content above 200 Mg ha^{-1}, high values even for meadows [66].

According to our study, organic fertilization and no fertilization are the best nutritional practices for mountain meadows. The use of inorganic fertilizers can increase yield when there is a favourable climate, but it lowers resilience. Further research is needed to evaluate if those results are consistent in the long term, as our study was carried out during only two years.

5. Conclusions

Meadows are complex systems where management practices have implications for soil nutrient availability.

Nitrogen availability depends both on management and climate. Inorganic fertilization is the least stable source, decreasing fast in the soil when there are more rainfall events; on the other hand, semi-extensive meadows have higher soil nitrogen stability even though it is applied in higher doses. Extensive meadows, despite lacking nitrogen fertilization, are more stable, relying less on climate.

Usually, phosphorus is the nutrient that limits yield, as is clearly shown in extensive meadows, which have reached an equilibrium between input and output. In intensive and semi-extensive meadows, we found lower phosphorus accumulation than the crop balance estimates, probably due to its blockage.

Potassium is clearly influenced by temperature, as we have found high differences between its concentration in June versus its concentration in February, even when the crop balance shows negative values. Only in extensive meadows is there always a potassium deficit, which could eventually cause potassium deficiency.

Carbon accumulation is also highly influenced by climate. Our results showed that when there is drought stress, meadows shift from a carbon sink into a carbon source. Extensive meadows were the only type that was able to accumulate carbon even in the drought year.

Further research will be needed to assess the long-term consequences of management, as this study is based on only two specific years.

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