THE PARADOXICAL PURSUIT OF SUSTAINABLE NITROGEN MANAGEMENT IN IRRIGATED HIGH-ELEVATION HAY MEADOWS

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ABSTRACT

Flood irrigated hay meadows are an integral, but often under-performing component of livestock operations in the Mountain West. Saturated soil and cool temperatures result in buildup an organic (O)-horizon, hindering forage production and nitrogen (N) cycling. For these reasons, many ranchers choose to fertilize with N regardless of large stores of N already in the soil. To improve long-term forage production in meadow systems, it is critical to understand the interaction between N cycling and soil N storage. Experiments were established in four locations in Wyoming and Colorado to monitor nutrient storage between fertilized and unfertilized irrigated meadows and unirrigated native rangelands. Total organic carbon (C) & N, microbial biomass C & N, potentially mineralizable C & N, dissolved organic C & N, nitrate (NO_3^-), and ammonium (NH_4^+) were assessed in each soil horizon to 1.5-m depth. Results confirmed significant accumulation of C and N in the O-horizon and significant differences in other C and N pools between the three systems. Unfertilized meadows stored significantly more stable and labile C and N than fertilized meadows and rangelands. Fertilized meadows stored comparable amounts of C and N to those in rangelands. An additional experiment assessed the impact of different field techniques (targeted grazing and tillage) to stimulate N mineralization from the O-horizon for improved fertility management. Results indicate heavy grazing and tillage stimulates N mineralization but damages the plant community, suggesting the need for other management techniques to manage soil N. A third experiment examined the effect of irrigation by assessing N mineralization with in-field incubation cores. The rate of N mineralization was highest 2-4 weeks after irrigation cessation, as soils warmed and became aerated. Avoiding long-term saturation during the growing season may improve N mineralization and plant utilization.

INTRODUCTION

Flood irrigated high-elevation hay meadows are integral to ranching operations in the Intermountain West as they provide critical winter forage for livestock production. Meadows developed in high mountain basins following the creation of canal and ditch systems to expand the irrigable footprint of land surrounding rivers and creeks (Peck & Lovvorn, 2001). High flow during spring snowmelt provides water to continuously flood meadows for 6-8 weeks from spring to mid-summer, after which one cutting of hay is harvested. Due to the short growing season and inefficient irrigation methods, yields are modest, averaging 1220-2240 kg ha^{-1} yr^{-1} (Ludwick & Rumburg, 1976).

To improve yields, ranchers often apply fertilizer nitrogen (N) at 60-90 kg ha^{-1} which increases forage yield to 3360-5600 kg ha^{-1} yr^{-1} (Ludwick & Rumburg, 1976).

However, the application of fertilizer N to sustain economic yields is paradoxical considering the abundance of organic N in meadow soils. Producers and researchers have noted the development of an organic (O)-horizon or “thatch” layer at the surface of meadow soils resulting from decades of seasonally flooded soil and short growing seasons which constrain microbial decomposition of residue (Lewis, 1957; Sims, 1979). However, few researchers have examined the effect of the O-horizon on nutrient cycling and N management in meadows. Only Siemer, (1979) noted 1220-2460 kg N ha^{-1} were stored in the top 10 cm of meadow soil. Later, Brummer et al., (2000) examined the effect of strip tillage and spike aeration to disturb the O-horizon and stimulate N mineralization but found no positive effect on yield.

With the increasing occurrence of drought, and the volatile nature of hay and fertilizer markets, producers must utilize sustainable management practices to maintain productivity of meadow forage systems. Therefore, the objective of this study is to examine the importance of the O-horizon in meadows as a fertility resource to reduce dependence on synthetic N for improved economic and agronomic sustainability in forage producing meadows.

MATERIALS AND METHODS

Carbon and Nitrogen Pools

To determine how long-term flood irrigation and fertilization have affected meadow soil organic matter (SOM), C and N storage and cycling, we identified four meadow systems in southern Wyoming and northern Colorado in fall 2021. Each meadow was flood irrigated and >2000-m elevation. At each meadow system we identified three management zones: 1) long-term irrigated meadow, 2) long-term fertilized and irrigated meadow, 3) unirrigated, unfertilized rangeland. All management zones were on the same soil series. At each location we excavated a soil pit to 1.5-m depth and took samples in each unique soil horizon from three adjacent pit faces according to Norton et al., (2004). Samples were placed on ice and transported to the lab for determination of total organic carbon (TOC), total nitrogen (TN), dissolved organic carbon (DOC), and nitrogen (DON), potentially mineralizable carbon (PMC), and nitrogen (PMN), nitrate (NO_3^-), and ammonium (NH_4^+). NO_3^-, and NH_4^+ were determined by extraction in 2M KCl followed by colorimetric analysis. PMN was analyzed using a 2-week anaerobic incubation (Waring & Bremner, 1964). PMC was analyzed using a 2-week aerobic incubation analyzed for CO_2 evolution (Zibilski, 1994). DOC and DON were determined by extraction in 0.5M K_2SO_4 and combustion analysis. MBC and MBN were determined using the fumigation method followed by extraction in 0.5M K_2SO_4 and combustion analysis (Horwath & Paul, 1994). TOC and TN were determined using combustion analysis.

Nitrogen Mineralization

To determine how management affects N-mineralization in meadows we established a randomized complete block field study at the Laramie Research and Extension Center (LREC) in fall 2021. Treatments included light, targeted grazing (145,000 kg liveweight ha^{-1} d^{-1}), heavy, targeted grazing (600,000 kg liveweight ha^{-1} d^{-1}), and rototilling to 4-cm depth. All treatments were initiated in fall 2021, and grazing treatments were repeated in fall 2022. Forage yield was determined by cutting a 1 × 15-m swath through the center of each plot in summer of 2022 and 2023. Soil samples were taken to 15-cm depth 7, 10, 13, and 20 months after treatment and analyzed for PMN, NO_3^-, and NH_4^+ using methods described above. PMN, NO_3^-, and NH_4^+ were summed to represent labile N.

To determine how irrigation affects seasonal N-mineralization, we implemented a field incubation on two of the four meadows mentioned above. The incubation was established in April 2023 immediately following soil thaw. Incubation cores were created by sampling a 4.5-cm diameter core encased in PVC plastic tubing to 22-cm depth. Ion exchange resin (IER) bags were placed at the bottom of the core to trap leached inorganic N. Grass was killed at the surface of the core. In this way, we created a field incubation that excludes inorganic N loss from leaching and plant uptake but allows natural exchange of water and gas to quantify season-long plant-available N mineralization. Cores were taken from the field, destructively sampled, and analyzed for NO_3^-, and NH_4^+ in soil and resins at nine pre-determined time points: following soil thaw, before irrigation, halfway through irrigation season, at irrigation termination, then 2 weeks, 4 weeks, 8 weeks, 12 weeks, and 16 weeks following irrigation termination.

Statistical Analysis

To determine differences in total storage of C or N to 1.5-m depth in meadow and rangeland soils, C or N mass (kg ha^{-1}) was determined for each horizon by adjusting for bulk density and horizon depth and summed to 1.5-m depth. Differences among treatments were determined using a linear mixed effects model using the “lme4” package in R version 4.1.1, with management as a fixed effect and site as a random effect. Means separation was performed using Tukey-adjusted pairwise comparisons at $\alpha = 0.05$. Differences in forage yield and labile N among grazing and tillage treatments were determined the same as above, with block being the random effect in the model.

N-mineralization rates were compared using a response feature analysis to determine the rate of change in $NO_3^- + NH_4^+$ concentration in cores between sampling points. The rate of change was then analyzed using a mixed-effects model as above, with sampling period as the main effect and location as a random effect. The estimated marginal mean and corresponding 95% confidence interval were determined using the “emmeans” package in R.

RESULTS AND DISCUSSION

Decades of continuous flood irrigation have resulted in an increase in both stable and labile C and N storage in unfertilized meadow soils compared to unirrigated rangeland soils (Table 1). However, meadows with long-term N fertilization in addition to irrigation had C and N pools that more closely resembled rangeland soils than unfertilized meadows. This may be a result of a priming effect of N fertilization, where increased bioavailable N provides enough microbial stimulation to allow for increased utilization of stable C and N pools which developed following irrigation (Kuzyakov et al., 2000).

Table 1: Total storage of C and N pools for three management systems to 150-cm depth. Values in brackets represent the standard error. Treatment means followed by different letters were significantly different at α = 0.05.

	Treatment					
	Unfertilized meadow		Fertilized meadow		Rangeland	
C or N Pool [a]	--------------- (kg ha^{-1}) ---------------					
TOC	219000 (18800)	a	167000 (14700)	b	134000 (18200)	b
TN	12200 (326)	a	8240 (711)	b	8590 (1060)	b
DOC	1430 (248)	a	610 (37.5)	b	1670 (478)	a
DON	112 (33.8)	a	34.6 (3.62)	b	58.5 (8.79)	a
MBC	3630 (670)	a	1750 (235)	b	1350 (153)	b
MBN	213 (48.5)	a	107 (14.1)	b	87 (11.9)	b
PMC	2300 (186)		1810 (266)		2090 (256)	
PMN	15.5 (4.88)	b	35.5 (8.91)	a	36.5 (8.00)	a
$NO_3^- + NH_4^+$	70.5 (11.6)	a	63.2 (8.9)	ab	50.6 (10.4)	b

[a] DOC = Dissolved organic carbon, DON = Dissolved organic nitrogen, MBC = Microbial biomass carbon, MBN = Microbial biomass nitrogen, PMC = Potentially mineralizable carbon, PMN = Potentially mineralizable N, TOC = Total organic carbon, TN = Total N

Some of the management tactics at the LREC experiment also resulted in stimulated microbial activity leading to increased N mineralization. Rototilling led to a significant increase in labile N in summer (10 months following treatment) and spring (20 months following treatment) (Figure 1). Heavy grazing also increased labile N, but not significantly more than the control.

Table 2: Forage yield (kg ha^{-1}) in meadows following rototilling, light grazing (145,000 kg liveweight ha^{-1} d^{-1}), and heavy grazing (600,000 kg liveweight ha^{-1} d^{-1}) in 2022 and 2023. All treatments were initiated in fall 2021, and grazing treatments were re-applied in fall 2022 Different letters denote significant differences among treatments at α = 0.05.

	2022		2023	
Treatment	------------Yield (kg ha^{-1})--------------			
Roto-till	1431	b	4143	a
Heavy Grazing	2975	ab	2243	b
Light Grazing	4101	a	3061	ab
Control	4699	a	3828	ab

Forage yields, however, showed the opposite response, where intense disturbance reduced yields (Table 2). Consecutive years of heavy grazing damaged the plant community and led to significantly reduced yields in 2023. Rototilling was similar, where excessive disturbance resulted in significantly decreased yields in 2022, but the plant community and yields recovered in 2023. Although more-intense disturbance increased labile N, it also reduced plant growth and negated potential benefits of increased N mineralization.

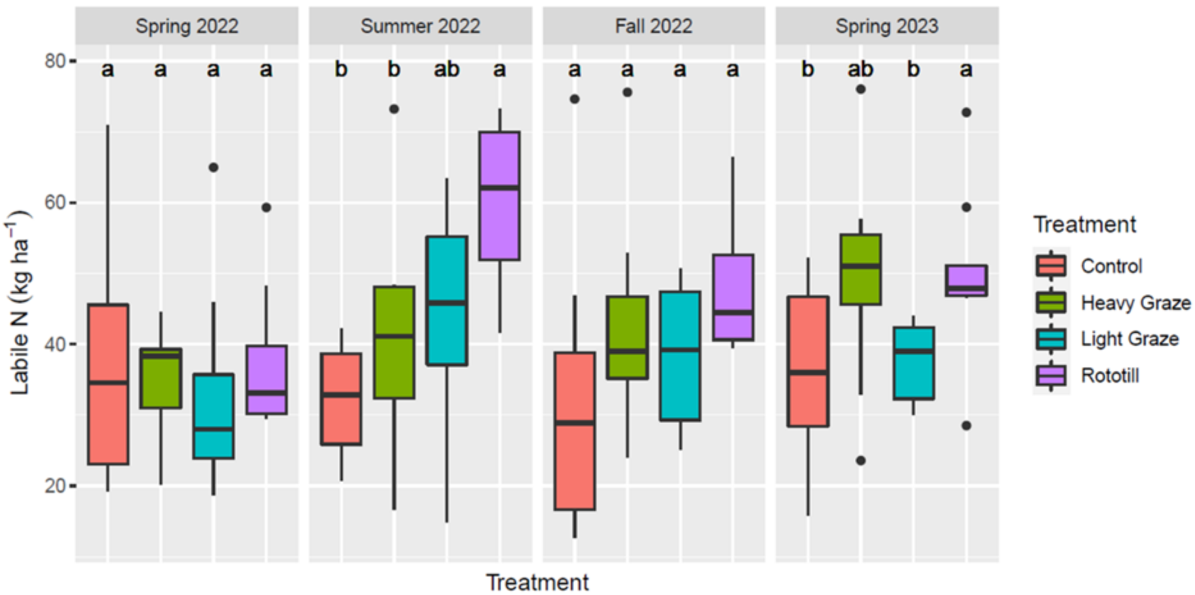

Figure 1: Labile N (kg ha^{-1}) (potentially mineralizable N + NO_3^- + NH_4^+) in meadows at LREC field experiment following rototilling, light grazing (145,000 kg liveweight ha^{-1} d^{-1}), and heavy grazing (600,000 kg liveweight ha^{-1} d^{-1}), for four seasons. All treatments were initiated in fall 2021, and grazing treatments were re-applied in fall 2022, four weeks prior to sampling. Different letters denote significant differences among treatments at each time point at α = 0.05.

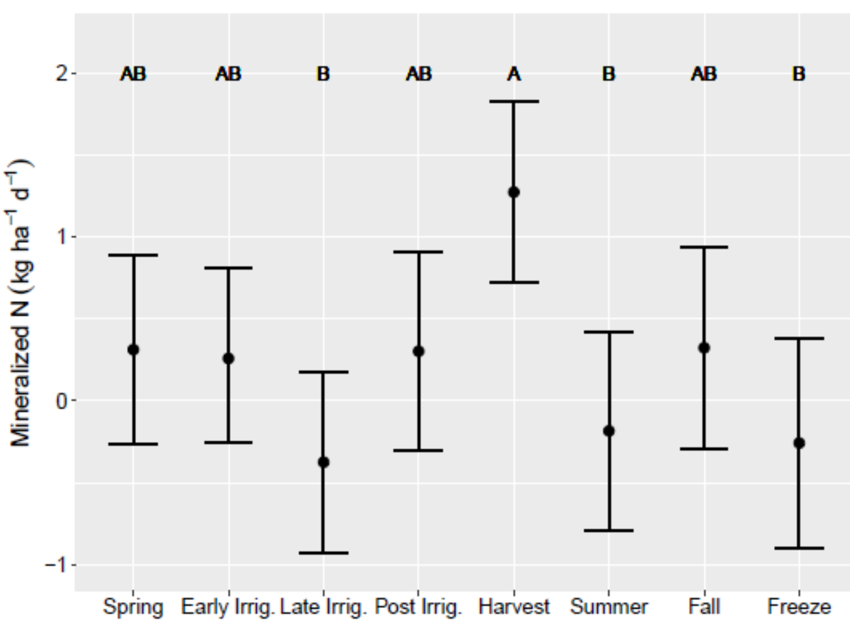

Figure 2: N mineralization rate (kg ha^{-1} d^{-1}) in meadows during eight unique periods of the frost-free season. Error bars denote 95% confidence interval. Different letters denote significant differences among periods at α = 0.05.

The inability of disturbance to increase forage yield through N mineralization means other practical management factors should be considered to leverage N mineralization for increased yield. Early research on meadows suggested that continuous irrigation and soil saturation decreased yield, and that staggered irrigations increased yield (Rumburg & Sawyer, 1965). This is partially due to increased N mineralization from microbial activity following periods of soil aeration between irrigation events. The results of our in-field incubation support this hypothesis, as we observed the highest rate of N mineralization in meadows during harvest, 2-4 weeks following irrigation termination, and the lowest rate of N mineralization 4-8 weeks after irrigation initiation when anaerobic conditions are most prevalent (Figure 2). Mineralization rates were also low in summer and late fall when drought or cold also become limiting factors for microbial activity. Therefore, producers should be cognizant to not over-saturate meadows during the growing season, when opportunities for efficient N mineralization and consequent utilization by the plant community are highest.

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