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ORIGINAL ARTICLE

Soil Fertility and Crop Nutrition

Fertilization strategy affects crop nutrient concentration and removal in semi-arid U.S. Northwest

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Abstract

Access to livestock manure is increasing in semi-arid cropping systems of U.S. Northwest prompting evaluation of fertilization strategies on regional production systems. A study conducted from fall 2012 to 2019 used: fall- or spring-applied dairy manure (56 Mg ha^{-1}), fall-applied composted dairy manure (33 Mg ha^{-1}), spring-applied urea or SUPERU (Koch Agronomic Services), and a control ($n = 6$) on a corn (*Zea mays* L.)–barley (*Hordeum vulgare* L.)–alfalfa (*Medicago sativa* L.)–alfalfa–alfalfa rotation. The effects of fertilization strategies on (a) soil nutrients, (b) crop tissue nutrient concentration and removal, and (c) digestibility and energy content of forages are discussed. Compost and manure additions increased corn silage N, P, K, respectively, by 0.86, 0.28, and 2.4 g kg^{-1} over other treatments; silage Ca and Mg were depressed 0.4 and 0.53 g kg^{-1} by manure applications. Barley grain $P_{removal}$ and $K_{removal}$ increased 5.10 and 7.65 g kg^{-1} under manure applications relative to urea and SUPERU treatments while crude protein (CP) (19.1 g N kg^{-1}) neared limits of high-quality malt extract (16–19 g N kg^{-1}). Compost and manure increased alfalfa K by 2.3 and 5.5 g kg^{-1} over other treatments, approaching levels of concern for hypocalcemia in dairy cattle (≥30 g K kg^{-1}). No major impact on corn silage or alfalfa quality parameters, were observed. Present Idaho nutrient removal estimates were representative of corn and alfalfa, but not barley in which observed N removal was 28% lower. In 17 of 18 instances, contrast testing suggested nutrient removal differed under organic amended treatments, suggesting nutrient removal modifiers in production systems receiving organic amendment may need established.

Abbreviation: Δ, difference from; ADF, acid detergent fiber; CF, crude fat; CP, crude protein; DTPA, diethylenetriaminepentaacetic acid; EPA, environmental protection agency; GDD, growing degree days; GRACEnet, greenhouse gas reduction though agricultural carbon enhancement network; NDF, neutral detergent fiber; NEL, net energy of lactation; OARDC, Ohio agricultural research and development center; RPC, relative percentage change; TDN, total digestible nutrients.

1 | INTRODUCTION

The Snake River plain in southern Idaho is home to an intensive dairy industry that is driving an increase in manure application to meet crop nutrient demands (Leytem et al., 2011). High quality alfalfa (*Medicago sativa* L.) and corn (*Zea mays* L.) silage forages are grown alongside commercial crops of potato (*Solanum tuberosum* L.), sugar beet (*Beta vulgaris* L.), wheat (*Triticum aestivum* L.), and malting barley (*Hordeum vulgare* L.) (USDA-NASS, 2021). Accessibility to manure and manure products and the proliferation of soil health-based C sequestration endeavors may increase producer interest in livestock manure or derivative products "for example, compost" to meet crop nutrient requirements (Chen & Vermeer, 2020; Sharma, 2019). As in other regions, land application of manure is commonly used as a disposal strategy with crop nutrition of subsidiary concern in this region. Consequently, producers need access to regional data on soil nutrient storage, forage quality, tissue nutrient concentration, and nutrient removal under different fertilization strategies to make informed management choices.

Manure products have been observed to influence crop nutrient density and increase soil nutrient stocks when not counterbalanced with nutrient removal during harvest (Lentz & Ippolito, 2012; J. J. Miller et al., 2015). Any build-and-maintain approach to nutrient management requires careful oversight to avoid regulative thresholds that restrict future applications to abate environmental concerns (Leytem et al., 2017; Sharpley et al., 2003). In addition, the dissimilarity between production systems with and without a history of organic amendment is of interest to producers in the prescription of drawdown plans and associated nutrient removal rates. Apart from organic amendment, plant-breeding endeavors alter nutrient use efficiency (Rajala et al., 2016), and produce cultivars of differing nutrient density (Murphy et al., 2008), and increased dry matter production (Woli et al., 2017). Regional nutrient management recommendations will benefit from periodic updates as relevant data become available and genetic advancement continues.

Evaluation of soil and plant nutrient contents is critical to forage cropping systems for determination of phytoavailability and later in ration formulation. When availability of a soil nutrient is insufficient or surplus, stunted growth, wasteful luxury consumption, toxicity or diminished forage quality can occur. For example, alfalfa is particularly subject to luxury consumption of soil K and may need to be addressed during ration formulation to minimize animal toxicity concerns like tetany (Jungers et al., 2019; Undersander et al., 2011). Availability of soil nutrients varies widely according to interrelated soil properties and the plant's nutrient requirements (Mahler, 2004). The application of manures, biochar, and composts return macronutrients and micronutrients to the soil, some of which are not supplied by typical N–P–K fertilizers. Absolute quantity and relative availability of nutrients from organic origin, that is, manure or manure products, vary, requiring recurring endeavors to determine crop response to organic product amendment.

Core Ideas

- Manure enhanced plant tissue concentration and removal of N, P, K while decreasing uptake of Ca and Mg in some crops.
- Manure increased crude protein and crude fat in corn but had no effect on forage quality parameters in alfalfa.
- Organic amendment should be considered in nutrient removal estimate tables.
- A typical regional manure application rate, 56 Mg ha^{-1}, rapidly necessitates P-based management.

In grasses, fertilization has little effect on forage digestibility outside of indirect effects such as sward composition (Ball et al., 2001; K. J. Moore et al., 2020). Conversely, alfalfa P and K contents have been positively correlated to top-dressed P and K applications (Hanson & MacGregor, 1966), and adverse physiological conditions have been observed in rabbits fed alfalfa produced on low-P fertility soil (Heinemann et al., 1957). Similarly, increased crude protein (CP) content of hay and corn silage is observed under both synthetic and organic N fertilization (Buxton et al., 1995; Lentz & Ippolito, 2012). Another study reported corn silage CP, digestible energy, and total digestible nutrients (TDN) were increased when application of N, P, and K were doubled, regardless of planting density (Alexander et al., 1963). In a different respect, increasing CP can be detrimental to quality in some commercial crops. In sugar beet, N application to maximize sucrose yield is below that which optimizes yield (Campbell, 2002). Similarly, malting barley extract is of highest quality when barley N content is between 16 and 19 g N kg^{-1}, and overapplication of N can result in surpassing this range and decreasing the crop's value (Jaeger, Zannini, Sahin, & Arendt, 2021). Calder and MacLeod (1968) reported in-vitro digestibility of alfalfa dry matter was significantly increased in the first cutting when under synthetic K fertilization. It is clear that fertilization practices may affect nutrient density and forage quality, having implications for crop commercial value and animal husbandry.

Plant tissue response to fertilization is more nuanced where manure or manure products, such as composts, separated solids or digestates are applied due to their compositional variability relative to applications of a single synthetic nutrient source. For example, while containing considerable

Ca, manure amendment is capable of decreasing Ca density in wheat and corn due to competition on exchange sites of the root's plasma membrane by supplying cations of similar valence and atomic radius (K and Mg) in high quantities (Cherney et al., 2002; Leytem et al., 2011; Marschner, 1995; Parsons et al., 2007). Furthermore, the interrelated increase in tissue K can be detrimental for animal wellbeing. Hypomagnesemia (grass tetany) can result from oversupplied soil K and the condition of hypocalcemia (milk fever) has been linked to increased dietary K intake through induction of metabolic alkalosis in dairy cattle (Goff & Horst, 1997).

Organic fertilization retains several advantages over synthetic fertilizers. Delayed mineralization of applied organic N may coincide with periods of rapid N acquisition and improve yields when N is otherwise limiting (Lehrsch & Kincaid, 2007; Lentz & Ippolito, 2012). Similarly, applied micronutrients can increase productivity and nutrient density over macronutrient fertilizers alone (Dimkpa & Bindraban, 2016; Rietra et al., 2017). Furthermore, long-term increases in relative yield have been reported under manure and manure + NPK additions over N or NPK additions alone (Huang et al., 2010). It should also not be overlooked that fractions of organic amendments may become stabilized and contribute to soil organic matter. Such increases in organic matter have been linked to soils' innate productive capacity and ancillary ecosystem services such as water retention and filtration.

Cropping systems in southern Idaho have been adjusted to support the expanding dairy industry by increasing forage production. Relative to 2000, planted corn land area in Idaho increased from 80,000 to 142,000 in 2022 while potato and sugarbeet production land area decreased, respectively, 20 and 24% (USDA-NASS, 2022). Further study of the impact manure and manure products have on forage system nutrient management in this regional scenario appears warranted. Additional insight into the acquisition and removal of nutrients in commercial crops would prepare regional producers considering supplementing nutritional requirements with the growing livestock manure resource. To prepare regional producers and nutrient management planners for this possibility, a location within the Greenhouse Gas Reduction through Agricultural Carbon Enhancement network research initiative in southern Idaho (Jawson et al., 2005) was identified as suitable for assisting in this endeavor as its implementation of different fertilization strategies followed since 2012 can be leveraged to determine the impact on nutrient uptake and removal (Dungan et al., 2017). Here, fertilization strategy refers to three of the four "R" pillars of nutrient management "source, rate, and time" (Fixen, 2020) which have been explored nonfactorially by the six nutrient management scenarios used in the study: fall or spring applications of dairy manure; fall application of dairy manure compost; and synthetic fertilization with either urea or SUPERU (Koch Agronomic Services). Therefore, the objectives of the present study were to characterize the influence fertilization strategies have on: (a) soil N, P, K, Ca, Mg, Mn, Na, bicarbonate extractable P, conductivity, and pH; (b) forage quality; and (c) the resulting tissue nutrient concentration and removal of crop biomass, N, P, K, Mg, Ca, and Mn in three regionally critical crops: corn, barley, and alfalfa.

2 | MATERIALS AND METHODS

2.1 | Site characterization

The location of study is within 5 km of Kimberly, ID. The climate of the region is considered semi-arid (Köppen classified Bsk, Peel et al. [2007]); mean annual temperature and precipitation are 9 ˚C and 240 mm, respectively. Soil at the location was identified as a Portneuf silt loam (coarse-silty, mixed, superactive, mesic Durinodic Xeric Haplocalcid) by web soil survey (Soil Survey Staff, 2021). Barley was grown in 2012 and the study commenced in the fall after harvest; the cropping rotation entered in 2013 and followed until 2019 was corn–barley–alfalfa–alfalfa–alfalfa. Plots 21.3 × 22.9 m were arranged in a randomized complete block design with four replications, each of which spanned the length of the field under a segment of the linear irrigation source ($n = 24$). Six fertilization strategies, that is, treatments, were considered: fall-applied drystack dairy manure (fall manure), fall applied composted drystack dairy manure (fall compost), spring-applied drystack dairy manure (spring manure), spring applied urea or SUPERU (urea stabilized with N-butyl-thiophosphoric triamide and dicyandiamide urease and nitrification inhibitors) (spring urea, spring SUPERU), and a no-treatment control (control). Drystack manure is stored outside in piles, that is, stacks, aboveground. Fertilizer applications were made based on the results of spring soil sampling using the University of Idaho Fertilizer Guidelines for spring barley, silage corn, and alfalfa (Brown et al., 2010; Mahler & Guy, 2007; Stark et al., 2002).

2.2 | Manure and fertilizer application

Manure and compost were applied at targeted dry weight application rates typical for the region: 56 and 33 Mg ha^{-1} for manure and compost treatments, respectively (Table 1). Rates were selected through conversations with regional custom manure applicators and compost manufacturers. The design of the study required nutrient sufficiency to be met in each year for all treatments except the control. Thus, spring soil sampling was performed to determine supplemental nutrient requirements. Manure and compost were applied in the fall (October or November) and manure was applied in the spring (April or May) prior to corn and barley. Manure application

TABLE 1 Manure and compost moisture and macronutrient (N, P, K, and C) concentration means for each instance of application

	Manure and compost properties								Applied macronutrients		
Treatment	**Year**	**Rate**	**Moisture**	**Total C**	**Total N**	**Total P**	**Total K**	**C/N**	**N**	**P**	**K**
		Mg ha^{-1}	g kg^{-1}						kg ha^{-1}		
Fall compost	2012	20.7	71	144	11.0	4.2	21.2	13	228	87	439
Fall manure	2012	56.8	529	281	18.7	6.4	31.1	15	062	364	1,766
Spring manure	2013	43.8	477	181	13.0	4.9	26.0	14	569	215	1,139
Fall compost	2013	28.4	150	119	12.3	3.3	18.1	10	349	94	514
Fall manure	2013	53.1	560	291	22.4	6.1	43.8	13	1,189	324	2,326
Spring manure	2014	48.0	605	275	19.5	7.0	59.0	14	936	336	2,832
Fall compost	2017	25.1	253	132	11.4	2.7	8.7	12	286	68	218
Fall manure	2017	53.1	562	174	12.5	4.5	25.3	14	664	239	1,343
Spring manure	2018	88.3	272	58	4.1	2.1	14.0	14	362	185	1,236
Fall compost	2018	29.8	114	60	5.3	3.0	13.7	11	158	89	408
Fall manure	2018	67.2	446	119	9.7	4.6	21.5	12	652	309	1,445
Spring manure	2019	54.3	554	187	8.3	7.6	18.0	23	451	413	977

Note. Application was performed on a dry weight basis and dry weight contents are reported.

was done by weighing the appropriate amount of manure per plot and spreading with a small plot manure spreader. Manure was immediately incorporated through disking to a 15-cm depth to minimize ammonia volatilization and P runoff losses over the winter; the fertilizer and control plots received the same tillage practice at this time. At each application event, manure samples were collected from each plot using three catch pans (0.5 × 0.6 m) within the plots during manure application and composited by plot. Following collection, manures were subsampled for water content and immediately frozen, lyophilized, and ground for analysis. Manure water content was determined gravimetrically on a 100-g subsample by drying at 105 ˚C for 24 h; total C and N content were determined via dry combustion with a Flash EA CHN analyzer (CE Elantech). Total elements (P, K, Ca, Mg, Zn, Mn, Na, and Fe) were determined via digestion of 0.5 g of manure using EPA digestion method 3052 and subsequent analysis by inductively coupled plasma optical emission spectrometry (Perkin Elmer Optima 7300 DV, Perkin Elmer). Manure and compost macronutrient properties and application rates are listed chronologically in Table 1.

Fertilizer applications were made based on results from spring soil sampling in late March or early April with six subsamples per plot, approximately 120 cores ha^{-1}, at 0-to-30-cm and 30-to-60-cm depths. The design of the study intended for nutrient sufficiency to be met in each treatment, apart from the control, which resulted in fertilizer applications to the compost treatment in some years (Brown et al., 2010; Robertson & Stark, 2003). Soils were air-dried, ground, and passed through a 2-mm sieve (US no. 10, Fisher Scientific Co.) before analysis for NO_3–N, NH_4–N, and Olsen ($NaHCO_3$ extractable) P. Soil NH_4–N and NO_3–N were determined by extraction with 2 mol L^{-1} KCl (5 g of soil in 50 ml of 2 mol L^{-1} KCl), shaken for 2 h, filtered and analyzed using QuickChem Methods 12-107-06-2-A (NH_4) and 12-107-04-1-B (NO_3) on a Lachat automated analyzer (Lachat Instruments, 1996). Olsen P was determined as $NaHCO_3$ extractable P following Olsen et al. (1954). Synthetic fertilizer applications over the rotation are detailed in Table 2.

2.3 | Agronomic practices

In 2013, corn (Pioneer P925HR HX1) was seeded on 16 May, at a rate of 86,000 seeds ha^{-1} using 76.2-cm row spacing. Glyphosate was applied at recommended rates on 5 and 26 June. Status (BASF Corporation) was also applied on 26 June. Barley (MillerCoors Moravian 69) was seeded in 2014 on 9 April at a rate of 4.1 million seeds ha^{-1} to a 17.8-cm row spacing. Colt, Sword (Loveland Incorporated) and Affinity BroadSpec (Dupont) were applied on 28 May. Alfalfa was seeded in 2015 on 16 April at a rate of 15 million seeds ha^{-1} to a 19.1-cm row spacing. Raptor (BASF Corporation) was applied to alfalfa on 18 June; in 2016, Gramaxone (Syngenta) and Sencor (Bayer) were applied on 18 March; in 2017 Metribuzen (Loveland Incorporated) and Gramoxone (Syngenta) were applied on 3 March. Corn (Pioneer P9188R) was seeded again in 2018 on 17 May using the previous rate and row spacing. Glyphosate (Loveland Incorporated) and Diflexx (Bayer) were applied on 15 May, glyphosate was applied a second time on 20 June. Barley (MillerCoors Moravian 69) was seeded in 2019 on 13 April at the previous rate and row spacing. Herbicide application in 2019 included Axial Star (Syngenta) and Affinity BroadSpec (Dupont) on

TABLE 2 Synthetic fertilizer applications made during the period of study

Date	Synthetic fertilizer applications				
	Treatment	**Source**	**N**	**P**	**K**
			kg ha^{-1}		
15 May 2013	Fall compost	Urea	168		
	SUPERU	SUPERU	186		
	Urea	Urea	186		
7 Apr. 2014	Fall compost	Urea	67		
	SUPERU	SUPERU	67		
	Urea	Urea	67		
27 Apr. 2018	Fall compost	MAP	7	12	
	Fall compost	K_2O			35
	SUPERU	MAP	24	44	
	SUPERU	K_2O			208
	Urea	MAP	24	44	
	Urea	K_2O			208
12 Apr. 2019	Fall compost	Urea	55		
	SUPERU	TSP		101	
	SUPERU	SUPERU	94		
	Urea	Urea	55		
	Urea	TSP		101	

Note. MAP, monoammonium phosphate; TSP, triple superphosphate. Manure applied treatments did not require supplemental synthetic fertilization to meet crop nutrient requirements.

13 May, and Roundup PowerMax (ScottsMiracle-Gro) on 21 August and 21 September. Irrigation was applied using a linear motion automated irrigation system. For all crops, irrigation rates were determined using the Washington State University Irrigation Scheduler (http://weather.wsu.edu/ism/) to meet estimated crop evapotranspiration (ET) rates (Wright, 1982).

2.4 | Crop yield and plant tissue sampling and analysis

Corn was harvested as silage, barley as malting grain with straw subsequently removed, and alfalfa for forage with two cuttings in 2015 and three cuttings in 2016 and 2017. Dates of crop harvest were: corn, 12 Sept. 2013; barley, 20 Aug. 2014; alfalfa, 18 July and 9 September in 2015, 26 May, 13 July, and 7 September in 2016, and 31 May, 10 July, and 15 September in 2017; corn, 24 Sept. 2018; barley, 8 Aug. 2019. For corn silage, a plot-scale forage harvester was used to harvest 18 m of a two-row strip to quantify yield and obtain tissue subsamples; bulk corn was harvested and removed by a commercial operator within 1 wk. For barley grain, a plot combine was used to harvest 18 m of an eight-row strip to quantify yield and obtain subsamples; bulk barley and straw were removed by a commercial operator within 1 wk. For alfalfa, a plot forage harvester was used to harvest 18 m of a seven-row strip for quantifying yield and obtaining subsamples; bulk alfalfa was cut, baled, and removed from the plots by a commercial operator within 1 wk.

Plant tissue samples were air-dried at 60 ˚C until stable mass and ground to 2 mm using a Wiley-Mill (Thomas Scientific); tissue nutrient concentrations were determined using EPA method 3052 and inductively coupled plasma optical emission spectroscopy (PerkinElmer Optima 4300 DV). Forage quality parameters of corn and alfalfa were determined by Dairyland Laboratories Inc. (Arcadia). Metrics of forage quality considered included: acid detergent fiber (ADF), neutral detergent fiber (NDF), CP, crude fiber (CF), lignin, starch, ash, total digestible nutrients (TDN), and net energy of lactation (NEL). Acid detergent fiber, NDF, and CF were determined using the filter bag technique (ANKOM methods 14|15|1, ANKOM Technology). Crude protein was determined by dry combustion (Tru-Mac N Macro Determinator, Leco Corporation). Lignin was determined as acid detergent lignin in a “Daisy” incubator (ANKOM method 9, ANKOM Technology). Starch was determined after hydrolyzing to produce dextrose and quantified by oxidation to hydrogen peroxide (YSI 2950D-1, YSI Incorporated Life Sciences). Ash content was determined by ignition using AOAC 942.05. Measures of energy were determined using summative equations developed by the Ohio Agricultural Research and Development Center (Ohio Agricultural Research and Development Center, 1992).

2.5 | Soil sampling for nutrient balances

Soil samples were taken after crop harvest each year using a hydraulic percussive sampling probe (9100 Ag Probe, AMS Inc.). Soil samples and laboratory analyses were completed on 15-cm depth increments; a depth of 0–30 cm is discussed after weighing 0-to-15-cm and 15-to-30-cm increments by bulk density and applying the resulting scalars to nutrient concentrations to permit their summation. Soils were air dried and ground to pass a 2-mm sieve before analysis of total N, P, K, Ca, Mg, Mn, Na, Olsen P, conductivity, and pH. Total N was quantified by dry combustion (FlashEA1112 CE Elanttech). Total P, K, Ca, Mg, Mn, and Na were determined after EPA digestion method 3052 by optical emission spectroscopy (PerkinElmer Optima 4300 DV). Olsen P was determined as described above. Electrical conductivity and pH were determined on a 1:1 soil–water mixture on a benchtop pH probe (R. O. Miller et al., 2013).

2.6 | Statistical analysis

All data manipulation required for statistical analysis was conducted in R (R Core Team, 2020) with support of the *tidyverse* package (Wickham et al., 2019) and its associated dependencies. Linear mixed effects models were developed by crop and dependent variable and fit using the *lme4* and *lmerTest* packages (Bates et al., 2015; Kuznetsova et al., 2017) using the maximum random effects structure approach presented by Barr et al. (2013); model terms were modified as needed to achieve model convergence. Fixed effects included treatment, year, and their interaction in applicable models; random effects included block in all models, and interactions of block with other factors. Model assumptions of homogeneity of variance and residual normality were assessed by normal histograms, QQ-plots, and residual plots with assistance from the *rcompanion* package (Mangiafico, 2020). In the case of forage quality, CP and ash content were respectively square root and log transformed to better satisfy the preceding assumptions. Significant model fixed effects were identified using the *F* test from type 3 ANOVA using the Satterwaithe approximation for denominator degrees of freedom. Orthogonal contrasts were performed for specific comparisons of interest (control vs. all; synthetic fertilizer vs. manure; urea vs. compost and manure; urea vs. SUPERU; and fall applied manure vs. spring applied manure) using the *emmeans* package (Lenth, 2020). All tests were considered significant at the .05 level. For soil nutrient status years were pooled, and data from 2012 were omitted as representative of the baseline condition after separately ensuring uniform starting values. For forage quality of corn silage, 2013 samples could not be assessed retroactively due to complications encountered during storage. Alfalfa cuttings were homogenized within each year prior to quantification of forage quality parameters. For tissue nutrient concentration, alfalfa cutting was incorporated into the model's random effect structure as a repeated measure. Observed N, P_2O_5, and K_2O removal rates were compared with Idaho estimated nutrient removal rates (Idaho nutrient removal rates: https://efotg.sc.egov.usda.gov/references/public/ID/CropRemovalRatesandFertilizerGuides_11132019.pdf) for each crop and treatment using *t* tests of their difference; the effect size was considered using Cohen's d and relative percentage change (RPC). In lieu of repeating nutrient removal data, tables with individual treatment comparisons to current Idaho crop nutrient removal estimates have been provided as Supplemental Material S1–S4.

3 | RESULTS AND DISCUSSION

3.1 | Climate and irrigation

Mean daily temperatures, cumulative growing degree days, precipitation/irrigation events and cumulative annual water input summarize environmental conditions during the period of study (Figure 1). Precipitation totals from 2013 to 2019 were 13.4, 36.8, 25.2, 35.8, 27.0, 32.4, and 26.6 cm, respectively. Irrigation totals from 2013 to 2019 were 60.5, 41.8, 61.6, 65.3, 58.4, 56.5, and 52, respectively. May to September average air temperatures were 10.6, 9.0, 10.2, 10.5, 10.0, 9.51, and 9.82 ˚C from 2013 to 2019. Total growing degree days (GDDs) accumulated in each year were 3,001, 3,059, 3,231, 2,971, 2,919, 2,842, and 2,639, respectively. As indicated in Figure 1, ∼10 cm more water was received in 2016 relative to other alfalfa years (2015, 2017). Cumulative GDD was highest in 2015 due to a comparatively warm June while July and August temperatures in 2017 were ∼1.7 ˚C higher relative to 2015 and 2016. There was a 28% difference in water received by barley in 2014 and 2019, although there were no recorded observations of drought stress.

3.2 | Soil nutrients

The effect of fertilization strategies on soil properties is shown in Table 3. Significant treatment differences were identified by ANOVA in 0-to-30-cm total soil N, total P, Olsen P, total K, and conductivity. Total N ranged from 1.0 to 1.3 g kg^{-1} with the greatest concentrations under both manure application timings. Contrasts of N indicated both manure and compost

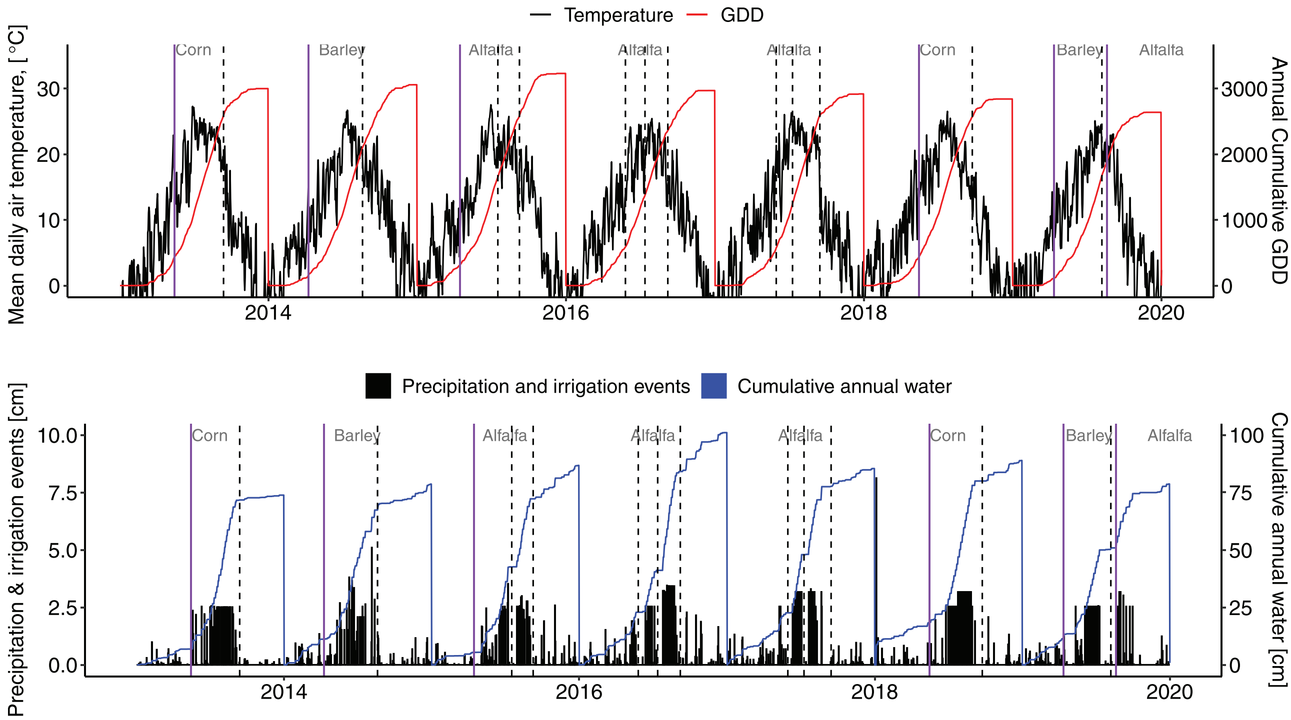

FIGURE 1 Mean daily temperatures, irrigation and precipitation events, and annual cumulative growing degree days (GDD) and water applied. Vertical solid purple lines indicate planting dates while vertical segmented lines indicate harvest and cutting dates

TABLE 3 Fall soil nutrient contents, conductivity, and pH at a depth of 0–30 cm under fertilization strategies

Treatment	Soil nutrient content										
	Total NO_3–N	Total N	Total K	Total Ca	Total Mg	Total P	Bicarb P	Total Mn	Total Na	EC	pH
	mg kg^{-1}	g kg^{-1}				mg kg^{-1}				dS m^{-1}	
Control	6.9	1.0	3.6	51.2	10.8	813.3	5.22	409.6	164.3	0.36	8.04
Fall compost	9.9	1.1	3.8	57.6	11.9	893.7	11.51	392.7	171.4	0.38	8.06
Fall manure	19.3	1.3	4.4	57.1	11.7	1,015.7	63.72	401.2	184.9	0.56	8.05
Spring manure	18.6	1.3	4.5	54.5	11.7	981.4	37.41	413.7	179	0.54	8.05
SUPERU	8.54	1.0	3.5	56.7	11.6	837.6	8.48	395.9	162.8	0.37	8.03
Urea	8.27	1.0	3.8	58.5	12	890.7	9.65	410.9	183.9	0.37	8.08
P value, Treatment	<.001	<.001	<.001	.674	.581	<.001	<.001	.951	.46	<.001	.65
Control vs. all	***	**	*	ns	ns	***	***	ns	ns	***	ns
Fertilizer vs. manure	***	***	***	ns	ns	***	***	ns	ns	***	ns
Urea vs. compost and manure	***	***	*	ns	ns	***	***	ns	ns	***	ns
Urea vs. SUPERU	ns	ns	ns	ns	ns	*	ns	ns	ns	ns	ns
Fall manure vs. spring manure	ns	ns	ns	ns	ns	ns	***	ns	ns	ns	ns

Note. ns, not significant. The ANOVA considered the fixed effect of treatment significant at the .05 probability level. Contrasts were performed at the .05 probability level after pooling years (2013–2019). Bicarbonate or Olsen P refers to the soil extract developed by Olsen et al. (1954).

*Significance of contrasts are indicated at $p < .05$.

**Significance of contrasts are indicated at $p < .01$.

***Significance of contrasts are indicated at $p < .001$.

applications increased N stock relative to synthetic fertilizers; neither timing of manure application nor use of the enhanced efficiency SUPERU significantly affected post-harvest soil N stock. Nitrogen needs of crops were met and partially met by manure and compost applications, respectively (www.uidaho.edu/extension; Table 2). Nevertheless, post-harvest NO_3–N is prone to leaching and post-harvest excesses should be minimized, especially as the region of study contains several groundwater nitrate priority areas (Idaho Department of Environmental Quality, 2020). Mean Post-harvest soil test NO_3–N was found to be 19.3 and 18.6 mg kg^{-1} under fall- and spring-applied manure fertilization treatments indicating the potential for substantive leaching at the application rate (56 Mg ha^{-1}) used in this study.

Manure and compost applications increased total soil P and Olsen P relative to synthetic fertilization strategies (Table 3). In Idaho, manure may be applied based on crop N needs until 0-to-30 cm soil Olsen-P exceeds set threshold levels (40 mg kg^{-1}, 80 mg kg^{-1}, 160 mg kg^{-1}) or the Phosphorus Site Index Rating exceeds "low", at which time applications must be based, respectively, on crop P uptake, crop P removal, or ceased entirely (USDA-NRCS, 2013). In the Idaho Phosphorous Site Index Rating, "low" indicates N-based manure application is permitted, "medium" indicates rates at crop P uptake are allowed, "high" decreases rates to one-half crop P uptake while "very high" restricts manure application (Leytem et al., 2017). Threshold levels were exceeded and approached, respectively, by fall and spring manure treatments but not synthetic fertilization or compost fertilization strategies (Table 3). Evidently, P-based management practices are rapidly necessitated at a 56 Mg ha^{-1} manure application rate. In contrast, compost application increased soil Olsen-P by ~2.45 mg kg^{-1} relative to synthetic treatments but remained well below the 40 mg kg^{-1} threshold. Contrasts for soil total P and Olsen-P were similar to each other; higher manure C content in the spring manure applications may have bound additional manure P and explain the comparatively lower Olsen-P relative to the fall application.

Total soil K responded to manure but not compost application, likely due to the lower application rate and K content of compost. Contrasts indicated higher soil K under manure relative to synthetic fertilizer strategies but no difference between manure application timing. Potassium is not typically limiting in soils of Idaho due to adequate soil K of geologic origin and irrigation water K contents. On the contrary, overapplication of K should be avoided in forage rotations in the region as K is prone to luxury consumption in alfalfa which can lead to hypocalcemia in dairy cattle (Stark et al., 2002). In the present study, manure applications increased soil conductivity by 0.18 dS m^{-1} relative to all other treatments, but remained below levels of concern for moderately tolerant plants (<2 dS m^{-1}) for regional soils under all treatments (Kotuby-Amacher, Koenig, & Kitchen, 2000; https://www.uidaho.edu/-/media/UIdaho-Responsive/Files/Extension/topic/nutrient-management/soils/saline-and-sodic-soils-in-idaho.pdf?la=en&hash=65566B2A5441705A83FB0B60D09C9C3CDBF6CC6E) and would be defined as USDA salinity class A (https://publications.metergroup.com/Sales%20and%20Support/METER%20Environment/Website%20Articles/electrical-conductivity-soil-predictor-plant-response%20(1).pdf). Saline/sodic soils are not widespread in southern Idaho, nevertheless, access to by-products of an expanding regional dairy industry may exacerbate salinity concerns, especially where or when irrigation is at deficit levels. There were no significant differences in 0-to-30-cm total soil Ca, total Mg, total Mn, total Na, or pH; likewise, all contrasts on these properties identified no significant differences (Table 3). A related study considering plant available soil micronutrient forms did report an increase in soil diethylenetriamine-pentaacetic acid (DTPA) Mg under manure application (Lentz & Ippolito, 2012) but characterization of micronutrient availability was beyond the scope of the present study.

3.3 | Crop yield

Crop yields were not affected by treatments, likely because of the sufficiency approach to the imposed fertilization strategies. Contrasts indicated the unfertilized control resulted in a lower yield relative to all fertilized treatments in 2014, 2015, 2017, and 2019. Differences in barley yield pertaining to synthetic fertilization vs. manure fertilization strategies were suggested in 2014; in 2019, barley yield under the spring urea treatment was significantly different from manure and compost treatments. For corn silage in both 2013 and 2018, considered contrasts did not identify significant differences (Table 4).

Elsewhere, Lentz and Ippolito (2012) applied manure to silage corn in the same region and reported increased yields and nutrient contents in 1 of 2 yr. Lehrsch and Kincaid (2007) reported a slight decrease in silage yield under higher single manure application rates (0, 29, and 72 Mg ha^{-1}), which they implied was due to high manure C content impeding soil N mineralization. In the present study, the mean corn silage yields in manure-amended treatments were numerically higher than other treatments, but not considered significantly different by the criteria of the study. It is possible that residual N following the alfalfa portion of the present study's rotation supplemented the following year (2018) of corn silage production as contrasts indicated no difference between the control and all other treatments (P = .519, Table 4). Still, growing season N mineralization in the region can be as high

TABLE 4 Mean crop yield for 2013–2019

Treatment	Standardized yield						
	Corn (2013)	Barley (2014)	Alfalfa (2015)	Alfalfa (2016)	Alfalfa (2017)	Corn (2018)	Barley (2019)
	Mg ha^{-1}						
Control	56.5	6.4	8.1	15.2	16.4	66.4	6.6
Fall compost	59.4	8.7	9.4	16.8	18.6	69.9	10.3
Fall manure	62.3	7.4	9.6	17.0	19.3	76.0	9.6
Spring manure	63.2	6.9	10.3	16.8	18.4	65.5	10.7
SUPERU	59.4	8.9	9.2	16.8	17.5	67.5	9.9
Urea	57.4	8.7	9.4	16.4	18.4	68.6	9.0
Contrasts							
Control vs. all	ns	**	*	ns	*	ns	***
Fertilizer vs. manure	ns	**	ns	ns	ns	ns	ns
Urea vs. compost and manure	ns	ns	ns	ns	ns	ns	*
Urea vs. SUPERU	ns	ns	ns	ns	ns	ns	ns
Fall manure vs. spring manure	ns	ns	ns	ns	ns	ns	ns

Note. ns, not significant. Yields were standardized to a consistent moisture content for reporting: Corn silage = 65% moisture; barley grain = 14.5% moisture; alfalfa hay = 12% moisture. Specified contrasts were conducted by year and were considered significant at the .05 probability level.
*Significance of contrasts are indicated at $p < .05$.
**Significance of contrasts are indicated at $p < .01$.
***Significance of contrasts are indicated at $p < .001$.

as 100 kg N ha^{-1} yr^{-1}, even where no organic amendment is used (Bierer et al., 2021; Koehn et al., 2021) and may be attributable to the lack of corn silage yield response in both 2013 and 2018. Both spring manure and fall manure fertilization strategies inadvertently depressed barley yield in 2014 after significant lodging of these treatments reduced harvestable grain. Indeed, excessive vegetative growth was commonly noted in field observation records. Lodging was not observed in 2019 and barley yields under manure-applied treatments were not significantly different from synthetic fertilization ($P = .155$). Despite this, when manure fertilization strategies were considered in conjunction with compost applications, barley yield responded positively to organic amendment ($P = .037$) compared with N fertilization using only urea. In no year were there significant differences in barley yield between urea and SUPERU or between timing of manure applications. Contrast testing indicated alfalfa yield responded to fertilization over the control in 2015, 2017, but not 2016; observed yields were 1.7 Mg ha^{-1} higher than the control over the 3 yr on average. Contrast testing did not indicate other differences in alfalfa yield due to fertilization strategy. Although not quantified, it is possible that soil N fixation in the 2nd year of alfalfa growth (2016) may have been adequate to remove the presence of a treatment effect on yield ($P = .095$). Indeed, another study in the same region reported higher soil N mineralization in 2016 relative to 2015 (Koehn et al., 2021).

3.4 | Nutrient removal

3.4.1 | Corn silage

The ANOVA indicated corn silage yield varied by year but not by treatment ($P = .739$) or their interaction ($P = .746$, Table 5). Significant differences in silage tissue concentration and removal of each nutrient under consideration were observed among treatments. Luxury consumption of N was evident from significant treatment differences in silage tissue N and $N_{removal}$ while yield remained unaffected. Tissue N was 0.87 g kg^{-1} higher under organic amendment relative to synthetic fertilizer which resulted in a 54 kg ha^{-1} increase in $N_{removal}$ over the control. Evidently, background soil N mineralization was sufficient for corn silage N needs during the period of study. However, in a previous report Lentz and Ippolito (2012) applied manure to silage corn in the same region and reported increases in both tissue N concentration and yield in 1 of 2 yr. Another comparable study reported a 30 kg ha^{-1} increase in silage $N_{removal}$ after a single compost or manure application in the same region (Lehrsch & Kincaid, 2007). In the present work, there were no appreciable differences in corn silage tissue N or $N_{removal}$ between urea and the stabilized SUPERU treatment or the timing of manure application (Table 5).

It was observed that corn silage tissue P and $P_{removal}$ increased 0.28 g kg^{-1} and 8 kg ha^{-1} under organic amendment

TABLE 5 Corn tissue nutrient concentration and removal under treatments of study

Corn	Yield (dry)	Nutrient concentration and removal											
		Tissue concentrations						Nutrient removal					
		N	P	Mg	Ca	K	Mn	N	P	Mg	Ca	K	Mn
	Mg ha^{-1}	g kg^{-1}					mg kg^{-1}	kg ha^{-1}					
Control	21.5	9.9	1.7	2.2	2.0	9.0	49.7	214.1	36.9	46.0	42.8	192.0	1.1
Fall compost	22.6	11.5	2.0	2.3	2.2	10.7	61.4	255.7	44.4	51.0	48.8	238.4	1.4
Fall manure	24.2	11.4	2.0	1.7	1.6	11.9	47.4	277.7	47.7	41.5	38.7	286.9	1.1
Spring manure	22.5	12.1	2.1	1.9	1.9	12.1	56.4	270.7	47.1	43.1	41.5	272.0	1.3
SUPERU	22.2	11.0	1.8	2.4	2.2	9.2	58.1	242.2	39.1	51.5	47.4	202.2	1.3
Urea	22.1	10.6	1.7	2.4	2.2	9.2	63.8	233.7	37.8	53.0	49.4	201.7	1.4
P value, Treatment	.739	.004	<.001	.004	<.001	<.001	.018	<.001	.024	.003	.048	<.001	.005
Control vs. all	ns	**	**	ns	ns	***	*	**	*	ns	ns	*	**
Fertilizer vs. manure	ns	**	***	***	***	***	*	**	**	***	**	***	*
Urea vs. compost and manure	ns	*	***	**	***	***	*	**	*	**	ns	**	ns
Urea vs. SUPERU	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
Fall manure vs. spring manure	ns	ns	ns	ns	*	ns	ns	ns	ns	ns	ns	ns	ns

Note. ns, not significant. ANOVA considered the fixed effect of treatment significant at the 0.05 probability level. Contrasts were performed at the .05 probability level after pooling years 2013 and 2018.

*Significance of contrasts are indicated at $p < .05$.

**Significance of contrasts are indicated at $p < .01$.

***Significance of contrasts are indicated at $p < .001$.

relative to synthetic fertilization (Table 5). Increased silage P concentration and $P_{removal}$ over synthetic fertilization has practical implications. Regional nutrient removal values used by nutrient management planners, established when application of manure products was less common, may need to be revised to consider land with manure or manure product application history. This is particularly relevant for managing soil P, as nutrient management plans may establish a soil P drawdown period or be restricted to $P_{removal}$-based manure application rates after soil test P thresholds are exceeded.

Corn silage tissue K and $K_{removal}$ increased following organic amendment fertilization strategies by 2.4 g kg^{-1} and 63.8 kg ha^{-1}, respectively, over urea and SUPERU use. It has been reported that increasing dietary K intake may induce metabolic alkalosis in dairy cattle leading to the condition of hypocalcemia (Goff & Horst, 1997). The concentration of corn silage K under manure-applied treatments in the current study (11.9 and 12.1 g kg^{-1}) was most similar to that imposed (11 g kg^{-1}) by Goff and Horst (1997) where only 10% of cows presented clinical hypocalcemia; increasing dietary K to 21 g kg^{-1} was substantially more detrimental, raising hypocalcemia incidence to 50%. Therefore, while corn silage K contents were elevated under both manure fertilization strategies, hypocalcemia incidence should remain low and may be addressed during ration formulation.

Remarkably, manure applications appeared to depress silage tissue Mg and Ca relative to synthetic fertilizer strategies in the present study (Table 5). Marschner (1995) described a nonspecific antagonism between K^+ and Ca^{2+} or Mg^{2+} due to competition for plant acquisition on exchange sites of the root plasma membrane and in the root cytoplasm for maintenance of intracellular electrical charge. It was suggested this K^+ and Ca^{2+} antagonism was causal to depressed wheat tissue Ca in a corn–wheat rotation receiving liquid dairy manure, despite measured increases in Melich-3 soil Ca contents (Parsons et al., 2007). Regionally, Lentz and Ippolito (2012) reported no difference in corn silage Ca but increased Mg after a single manure application of 42 Mg ha^{-1} in 1 of 2 yr. Even so, others have reported decreased corn silage tissue Mg or Mn with increasing manure or compost application rates (Leytem et al., 2011; A. Moore et al., 2010). In both preceding studies, reduced corn silage tissue Mg or Mn was attributed to chelation with C applied in either manure or compost. In our own study, corn silage Ca and Mg declined by 0.5 and 0.6 g kg^{-1} for manure treatments vs. fertilizer. An additional analysis of Pearson's correlations resulted in a significant ($r = -.51$, $P = .002$) association between silage tissue Ca and soil K, but not tissue Mg or tissue Mn (data not shown). Although corn silage Ca was depressed by the manure fertilization strategies, feed recommendations for lactating dairy cows (7.5–10 g Ca kg^{-1}) would require mineral supplementation under all treatments in this study and would likely be addressed during ration formulation.

TABLE 6 Barley grain nutrient concentration and removal under treatments of study

		Nutrient concentration and removal											
		Tissue concentrations						Nutrient removal					
Barley	**Yield (dry)**	**N**	**P**	**Mg**	**K**	**Ca**	**Mn**	**N**	**P**	**Mg**	**K**	**Ca**	**Mn**
	Mg ha^{-1}	g kg^{-1}				mg kg^{-1}		kg ha^{-1}					
Control	5.3	13.1	3.2	1.4	5.7	770.4	19.6	70.3	17.2	7.6	30.2	4.1	0.1
Fall compost	7.9	15.7	3.6	1.5	6	881.4	20.2	124.8	28.5	11.8	48.1	7	0.2
Fall manure	7.0	19.2	4.7	1.7	7.4	978.2	23.4	133.9	32.3	11.9	52.5	6.7	0.2
Spring manure	7.2	19.1	4.4	1.6	7.1	891.3	22.8	135.1	30.9	11.6	51.7	6.2	0.2
SUPERU	7.7	15.3	3.4	1.5	5.9	810.4	20.6	117.7	26.6	11.6	45.8	6.3	0.2
Urea	7.3	14.3	3.6	1.6	5.9	816.8	20.8	104.2	26.4	11.3	43.1	6	0.2
P value, Treatment	<.001	<.001	<.001	.003	<.001	.187	.061	<.001	<.001	<.001	<.001	.006	<.001
Control vs. All	***	***	***	*	*	ns	ns	***	***	***	***	**	***
Fertilizer vs. manure	ns	***	***	*	***	ns	*	***	**	ns	*	ns	ns
Urea vs. compost and manure	ns	***	***	ns	*	ns	ns	***	*	ns	*	ns	ns
Urea vs. SUPERU	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
Fall manure vs. spring manure	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns

Note. ns, not significant. ANOVA considered the fixed effect of treatment significant at the .05 probability level. Contrasts were performed at the .05 probability level after pooling years 2014 and 2019.
*Significance of contrasts are indicated at $p < .05$.
**Significance of contrasts are indicated at $p < .01$.
***Significance of contrasts are indicated at $p < .001$.

3.4.2 | Barley

In barley, ANOVA identified a significant effect of fertilization strategy on barley yield ($P < .001$), most likely due to low yield under the control (Table 6). As a result, treatment effects were present for removal of each nutrient under consideration. Lodging was observed in both manure-applied treatments in 2014, but neither in 2019, and reduced harvestable yields. Significant differences in barley tissue N were observed in the following contrasts: control vs. all, fertilizer vs. manure, and urea vs. compost and manure. Others have reported a significant positive correlation between N application rates and barley crude protein (CP, i.e., N) levels (Chang et al., 1993; J. J. Miller et al., 2015). In the present study, barley tissue N under the manure fertilization strategies (19.1 g kg^{-1}) was considerably above that of compost (15.7 g kg^{-1}) and both synthetic fertilizer strategies (15.3, 14.3 g kg^{-1}, Table 6). In southern Idaho, regional barley production is for malt extract for which CP (N) content is important to maintain extract quality. High quality malt extract is obtained from barley CP content ranging from 16 to 19 g N kg^{-1}, with lower or higher CP contents risking lower extract yield (Jaeger et al., 2021). Clearly, manure application at the rate used in this study (56 Mg ha^{-1}) can rapidly result in malting barley N contents at the upper extent of this range. Therefore, it is advised that lower manure application rates are used where malting barley is grown. Relative to the synthetic fertilizers (average 3.5 g P kg^{-1}), barley grain tissue P concentration increased under either fall- (4.7 g P kg^{-1}) and spring (4.4 g P kg^{-1})-applied manure and to a lesser extent under compost (3.6 g P kg^{-1}) applications (Table 1). Barley grain $P_{removal}$ increased over synthetic fertilization by 5.1 kg ha^{-1} under manure applications while barley $K_{removal}$ removal increased by 7.7 kg ha^{-1}(Table 6). Tissue Mg concentrations increased 0.1 g kg^{-1} in manure vs. fertilizer treatments. This was attributed to higher grain tissue concentrations as barley yields were not significantly different across fertilization strategies apart from the control.

There were no differences in barley tissue Ca for any treatment (P = .187). Unlike in corn silage, barley tissue Ca and Mg were not depressed under the manure fertilization strategies. However, some research has reported this antagonism in whole plant (wheat) but not grain tissues suggesting the antagonism may primarily, or at least initially, manifest in vegetative tissues (Parsons et al., 2007). Considered contrasts of the present study did not identify significant differences in barley tissue concentration or removal of any nutrient between timing of manure application or between synthetic fertilizer products; though some influence of the enhanced efficiency SUPERU product on barley $N_{removal}$ appears plausible (P = .116, Table 6).

TABLE 7 Alfalfa tissue nutrient concentration and removal under treatments of study

Alfalfa	Yield (dry)	Nutrient concentration and removal											
		Tissue concentrations						Nutrient removal					
		N	P	Mg	Ca	K	Mn	N	P	Mg	Ca	K	Mn
	Mg ha^{-1}	g kg^{-1}					mg kg^{-1}	kg ha^{-1}					
Control	4.3	29.4	2.0	4.2	19.5	24.5	39.06	129.02	8.92	18.22	84.75	106.97	0.17
Fall compost	4.9	29.7	2.2	4.2	18.4	26.0	38.52	146.39	10.73	21.04	90.22	128.39	0.19
Fall manure	5.1	30.8	2.5	4.1	17.7	28.2	34.38	156.57	12.75	20.65	90.37	142.78	0.17
Spring manure	5.0	29.7	2.6	4.1	17.1	30.2	36.22	147.2	12.87	21.09	85.59	151.49	0.18
SUPERU	4.8	29.6	2.2	4.3	19.2	23.3	37.74	142.42	10.48	20.4	91.99	112.67	0.18
Urea	4.8	28.6	2.1	4.5	18.9	23.3	37.66	139.64	10.26	21.98	91.68	113.44	0.18
P value, Treatment	.031	.019	<.001	.264	.013	<.001	.116	.006	<.001	.235	.605	<.001	.44
Control vs. all	***	ns	**	ns	*	ns	ns	**	***	*	ns	**	ns
Fertilizer vs. manure	ns	*	***	ns	*	***	ns	*	***	ns	ns	***	ns
Urea vs. compost and manure	ns	**	**	*	ns	***	ns	*	*	ns	ns	***	ns
Urea vs. SUPERU	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
Fall manure vs. spring manure	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns

Note. ns, not significant. ANOVA considered the fixed effect of treatment significant at the .05 probability level. Contrasts were performed at the .05 probability level after pooling years 2015, 2016, and 2017.
*Significance of contrasts are indicated at $p < .05$.
**Significance of contrasts are indicated at $p < .01$.
***Significance of contrasts are indicated at $p < .001$.

3.4.3 | Alfalfa

Analysis of variance recognized a significant effect of fertilization strategy on alfalfa yield ($P = .031$) though subsequent contrasts indicated no difference between fertilization strategies aside from the control. As fertilizer from any source was not applied in the fall or spring before alfalfa was seeded, the yield difference may be explained by residual N from prior application of treatments or additional nutrient return via belowground root tissue as the preceding year's barley yield response to fertilization was considerable. Elsewhere, response of alfalfa yield to fertilization has varied by intrinsic soil fertility. In Wisconsin, greater alfalfa yield response relative to synthetic fertilization was observed in lower fertility soils receiving manure applications at equivalent P and K rates of synthetic fertilizer treatments used in this Wisconsin study (Kelling & Schmitt, 2003). Similarly, Lloveras et al. (2004) observed alfalfa yield response to manure application in a low but not high fertility soil, delineated from higher macronutrient and micronutrient concentrations, in Spain. In the current study, contrasts suggested some difference in alfalfa tissue N concentration between organic and synthetic fertilization strategies, albeit minor (1 g kg^{-1}, Table 7). Fertilization strategy had a larger impact on alfalfa tissue P, with higher concentrations under both manure applications (2.5 and 2.6 g P kg^{-1}) relative to compost (2.2 g P kg^{-1}) or synthetic fertilization (2.2 and 2.1 g P kg^{-1}); presumably due to compost having a lower P concentration and being applied at a lower rate than manure (56 vs. 33 Mg ha^{-1}, Table 1). Organic-amended treatments increased alfalfa tissue P concentration by 0.28 g P kg^{-1} on average, likely due to higher P application rates (Tables 1 and 2), and luxury consumption as there were no differences in alfalfa yield between organic-amended and synthetic fertilization strategies (Table 4). More consequentially, alfalfa K contents sharply increased in response to both manure and compost fertilization. All treatments exhibited alfalfa K contents above the reported regional range (17–20 g K kg^{-1}) (Mahler, 2002). Moreover, alfalfa tissue K contents of manure-applied treatments (mean 29.2 g K kg^{-1}) had increased by 5.5 g kg^{-1} relative to synthetic fertilization and control; compost application increased alfalfa K by only 2.3 g kg^{-1} by comparison (Table 7). Alfalfa K contents over 30 g kg^{-1} are of concern for exacerbating hypomagnesemia or inducing metabolic alkalosis, causal to hypocalcemia, in dairy cattle (Goff & Horst, 1997). Clearly, manure applications at the target rate of this study (56 Mg ha^{-1}) will rapidly present this forage quality concern in alfalfa and suggests rate reductions and continual monitoring where manure-based fertilization strategies are used to avoid losses in dairy productivity. As in corn silage, a slight depression (1.6 g kg^{-1}) was observed in alfalfa tissue Ca with manure application over all other fertilization strategies (Table 7). There were no

TABLE 8 Current Idaho recommended nutrient removal rates of N, P_2O_5, and K_2O for alfalfa hay, spring malting barley, and corn silage at standardized mass fractions

Crop	Idaho crop removal estimates, September 2022						
	Mass fraction	N		P_2O_5		K_2O	
	H_2O 100^{-1}	lbs ton^{-1}	kg Mg^{-1}	lbs ton^{-1}	kg Mg^{-1}	lbs ton^{-1}	kg Mg^{-1}
Alfalfa, hay	10	58.02	29.01	10.64	5.32	63.04	31.52
Barley spring, malt	13	46.46	23.23	15.80	7.90	11.98	5.99
Corn silage	71	23.45	11.72	8.66	4.33	23.83	11.91

significant contrasts in alfalfa tissue concentration or removal of any nutrient between synthetic fertilizers or fall and spring timing of manure application.

3.4.4 | Idaho state recommendations

A separate analysis was completed to compare nutrient removal rates observed in the present study and the current estimates used in Idaho (Table 8). Current Idaho estimated nutrient removal rates for N, P_2O_5, and K_2O were subtracted from nutrient removal values for each observation of the present study. One sample *t* tests were conducted to determine if the mean difference was equal to 0. These *t* tests were conducted for each crop on: (a) noncontrol treatments holistically and (b) individual treatments. In each case, the mean removal rate, *P* value, RPC, and Cohen's d are reported for each treatment as Supplemental Material S1–S3. A linear model fitting the difference as a function of treatment also permitted orthogonal contrast testing as done elsewhere in the study.

While considering all fertilized treatments, observed N, P_2O_5, and K_2O removal rates for alfalfa and the P_2O_5 removal rate for corn silage were not significantly different from current Idaho estimates (all $P > .100$; Supplemental Material S3; Figure 2). Therefore, there was no evidence to suggest updating Idaho alfalfa nutrient removal rates and corn P_2O_5 removal if a modest representation of several fertilization strategies is desired (Figure 2). Corn N and K_2O removal rates were significantly different from current Idaho estimates, although the effect size was considered small (Cohen's d ± 0.4, RPC ± 8.0; Supplemental Material S1) and may not justify update of the estimate. Still, corn removal of P_2O_5 and K_2O between manure-applied treatments and synthetic fertilization treatments were recognized as significantly different by orthogonal contrast testing.

Barley N removal for each fertilization strategy fell well below the current Idaho estimate as the RPC was −27.9% for noncontrol treatments (Supplemental Material S2). Observed barley removal rates of P_2O_5 and K_2O were increased by 2.4 and 2.8 kg Mg^{-1} on average over respective current Idaho estimates. Therefore, an average barley yield (7 Mg ha^{-1}) could result in a discrepancy in actual and predicted P_2O_5 removal by up to 17 kg ha^{-1} yr^{-1}. These findings support the re-evaluation of Idaho spring malting barley nutrient removal estimates. Considering the current barley estimate is based on a synthesis from 2003 (Robertson & Stark, 2003), it may not capture breeding endeavors in the preceding years to increase malt extract quality by reducing protein content.

In zero of nine instances were significant differences indicated in spring urea vs. spring SUPERU, or spring manure vs. fall manure contrasts (Supplemental Material S1–S3). The lack of response was interpreted to contradict the separation of these respective treatments in nutrient removal rates. In contrast, in 17 of 18 instances significant differences were suggested by the fertilizer vs. manure, and urea vs. compost and manure contrasts. Therefore, there may not be a need to specify separate removal rates for use of enhanced efficiency N fertilizer, nor for separate timing of manure applications. However, a difference in organic and inorganic fertilization strategies was suggested.

In response, a final set of *t* tests were conducted grouping treatments into organic and synthetic fertilization strategies: (a) fall manure, spring manure, and fall compost; and (b) spring urea and spring SUPERU, respectively. The resulting nutrient removal estimates, confidence intervals, *P* values, and suggested adjustment factors for application to current Idaho crop nutrient removal rates have been reported (Table 9). In corn, N removal under organic amendment aligned with the current Idaho estimate while N removal under synthetic fertilization was ~8% lower. Organic amendment and synthetic fertilization were split 6% over and 8% below the current Idaho P_2O_5 removal estimate, respectively, while removal of K_2O was ~2 kg Mg^{-1} higher under organic amendment than the current Idaho estimate. In barley, N removal estimates under synthetic- and organic-amended fertilization strategies were 14.8 and 18.1 kg Mg^{-1}, this observation suggests decreasing the current N removal estimate by at least 22%. In alfalfa, the P_2O_5 removal estimate for organic-amended treatments was numerically 0.3 kg Mg^{-1} higher than the current Idaho estimate but was not considered significantly different at the .05 probability level. Estimated alfalfa K_2O removal was 9.1% higher than the

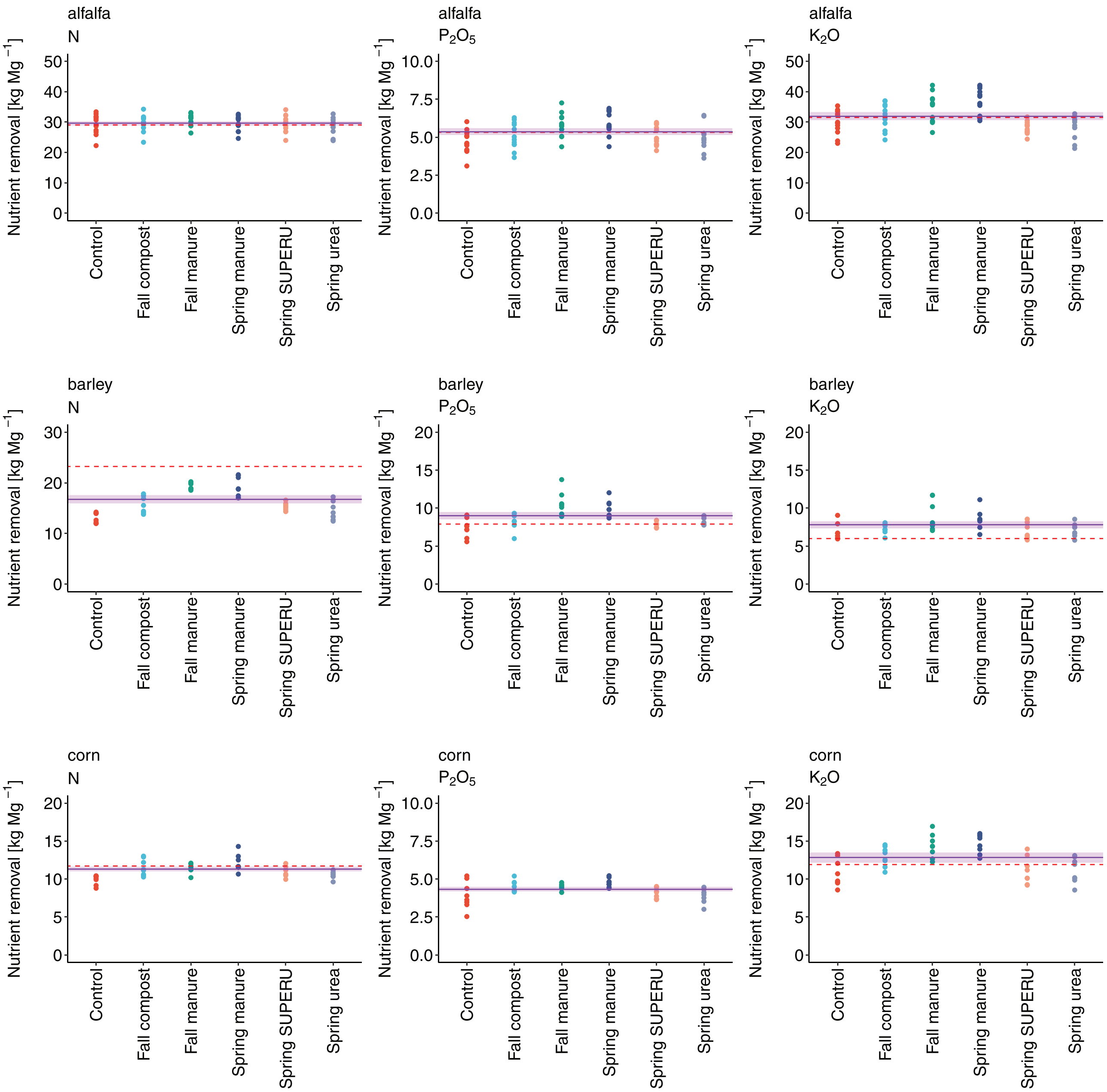

FIGURE 2 Annual crop N, P_2O_5, and K_2O removal rates by each fertilization strategy; for alfalfa, biomass from multiple cuttings were summed each year and the mean annual nutrient concentrations were used. The horizontal red lines indicate current Idaho nutrient removal values for each crop and nutrient. The horizontal purple lines and shaded ribbons indicate the observed mean and .05 probability level confidence interval for nutrient removal for all treatments excluding the control

current Idaho estimate under organic-amended treatments while synthetically fertilized treatments were 10% lower.

The impact of organic amendment on nutrient removal was not consistent among crops or macronutrients. This observation suggests either: (a) establishment of a separate set of estimated nutrient removal rates for organically amended production systems; or (b) crop and nutrient specific modifiers which can be applied to production systems using organic amendment. Pertinently, synthetically fertilized treatments did not always align with the current Idaho nutrient removal estimates. Thus, it may be justifiable to redefine baseline removal estimates before prescribing adjustment factors for organically amended systems. A table providing N, P_2O_5, and K_2O removal rates observed under synthetic fertilization in the present study and the corresponding organic amendment adjustment factors has been provided as SupplementalMaterial S4.

TABLE 9 Annual crop N, P_2O_5, and K_2O removal rates under organic (fall manure, spring manure, fall compost) and inorganic (spring SUPERU, spring urea) fertilization strategies

	N					P_2O_5					K_2O				
Crop	**Estimate**	**0.95 CI_{lower}**	**0.95 CI_{upper}**	***P***	**Adjustment factor**	**Estimate**	**0.95 CI_{lower}**	**0.95 CI_{upper}**	***P***	**Adjustment factor**	**Estimate**	**0.95 CI_{lower}**	**0.95 CI_{upper}**	***P***	**Adjustment factor**
	kg Mg^{-1}					kg Mg^{-1}					kg Mg^{-1}				
Corn															
Current Idaho estimate	11.7					4.3					11.9				
Fall manure, spring manure, fall compost	11.7	11.3	12.1	.822	na	4.6	4.5	4.7	<.001	6.0	14.0	13.3	14.6	<.001	17.3
Spring SUPERU, spring urea	10.8	10.5	11.1	<.001	–7.9	4.0	3.7	4.2	.003	–8.4	11.1	10.2	12.0	.068	na
Barley															
Current Idaho estimate	23.2					7.9					6.0				
Fall manure, spring manure, fall compost	18.1	17.2	19.1	<.001	–22.0	9.7	9.0	10.4	<.001	22.5	8.3	7.6	9.0	<.001	38.4
Spring SUPERU, spring urea	14.8	14.0	15.5	<.001	–36.3	8.0	7.8	8.3	.307	na	7.1	6.6	7.6	<.001	18.7
Alfalfa															
Current Idaho estimate	29.0					5.3					31.5				
Fall manure, spring manure, fall compost	30.0	29.2	30.9	.015	3.5	5.6	5.3	5.9	.056	na	34.4	32.8	36.0	.001	9.1
Spring SUPERU, spring urea	28.8	27.6	30.0	.749	na	5.0	4.7	5.3	.048	–5.9	28.3	27.0	29.5	<.001	–10.3

Note. na, not applicable. Suggested adjustments to current Idaho nutrient removal estimates are given. One sample *t* tests considered a significant difference from the current removal values at the .05 probability level

TABLE 10 Corn silage and alfalfa forage quality parameters under treatments of study. The ANOVA considered the fixed effect of treatment significant at the .05 probability level

Crop	Forage quality parameter								
	ADF	NDF	TDN	CP	CF	Lignin	Starch	Ash	NEL
	g DM kg^{-1}								Kcal kg^{-1}
Corn									
Control	220.4	367.0	720.4	72.0	23.2	25.2	368.4	50.2	74.77
Fall compost	225.9	383.1	714.0	78.7	25.0	25.8	337.6	52.6	74.06
Fall manure	204.5	351.1	726.8	79.2	26.2	22.6	364.6	55.9	75.48
Spring manure	203.7	357.4	725.8	84.6	26.3	23.1	346.1	54.7	75.37
SUPERU	215.2	368.9	723.0	73.6	25.2	25.8	360.6	48.4	75.06
Urea	220.7	372.0	716.3	72.3	23.6	26.4	360.0	51.7	74.32
P value, treatment	.273	.164	.650	.006	.005	.465	.523	.286	.648
Control vs. all	ns	ns	ns	*	**	ns	ns	ns	ns
Fertilizer vs. manure	ns	ns	ns	***	**	ns	ns	ns	ns
Urea vs. compost and manure	ns	ns	ns	**	**	ns	ns	ns	ns
Urea vs. SUPERU	ns	ns	ns	ns	ns	ns	ns	ns	ns
Fall manure vs. spring manure	ns	ns	ns	ns	ns	ns	ns	ns	ns
Alfalfa									
Control	311.6	366.1	601.4	208.5	16.8	64.5	8.3	108.0	61.52
Fall compost	325.5	377.6	595.1	213.9	15.1	65.8	8.8	106.1	60.82
Fall manure	322.1	379.9	592.0	216.7	15.4	64.8	7.9	110.0	60.48
Spring manure	326.6	386.1	586.0	214.7	14.8	66.5	8.0	111.6	59.80
SUPERU	318.7	373.3	604.4	212.1	16.4	65.3	9.3	101.3	61.85
Urea	321.3	377.7	598.2	208.4	15.1	66.9	11.1	101.7	61.16
P value, treatment	.924	.917	.613	.889	.692	.724	.966	.385	.598
Control vs. all	ns	ns	ns	ns	ns	ns	ns	ns	ns
Fertilizer vs. manure	ns	ns	ns	ns	ns	ns	ns	**	ns
Urea vs. compost and manure	ns	ns	ns	ns	ns	ns	ns	*	ns
Urea vs. SUPERU	ns	ns	ns	ns	ns	ns	ns	ns	ns
Fall manure vs. spring manure	ns	ns	ns	ns	ns	ns	ns	ns	ns

Note. ADF, acid detergent fiber; CF, crude fat; CP, crude protein; NDF, neutral detergent fiber; NEL, net energy of lactation; ns, not significant; TDN, total digestible nutrients. Contrasts were performed at the .05 probability level after pooling years (2018, corn; 2015, 2016, 2017, alfalfa); in the case of alfalfa, tissue cuttings were homogenized. Forage quality of corn in 2013 could not be assessed retroactively due to complications encountered during storage.

*Significance of contrasts are indicated at the following level: $p < .05$.

**Significance of contrasts are indicated at the following level: $p < .01$.

***Significance of contrasts are indicated at the following level: $p < .001$.

3.5 | Forage quality

3.5.1 | Corn

Analysis of variance identified a significant treatment effect on corn silage CP and CF, but not ADF, NDF, TDN, lignin, starch, ash, or NEL (Table 10). Conducted contrasts suggest compost and manure applications increased corn silage CP and CF. Relative to both synthetic fertilization strategies, silage CP was 5.8, 6.3, and 11.7 g kg^{-1} higher under compost application, fall and spring manure application timings, respectively. Mean corn silage CP under the spring manure application treatment was numerically higher than the fall application counterpart but was not considered significant by the criteria of this study ($P = .117$ vs. $P \leq .050$). A similar outcome was reported by Grabber et al. (2014) under continuous corn where CP yield was not affected by fall or spring manure applications. Still, fall applications leave an elongated window for N losses which may provide comparatively less N to the successive crop in some years. In the present study, corn silage CF was raised an average of 2.3 g kg^{-1} under compost or manure amendment and SUPERU use compared with either the control or urea treatments (Table 10). While compost or manure amendment did not significantly affect corn silage ADF, NDF, or NEL, the increased CF under manure application does suggest a minor effect on silage energy content.

3.5.2 | Alfalfa

The ANOVA indicated fertilization strategy did not have a significant effect on alfalfa forage quality parameters (Table 10). Alfalfa CP was unlikely to respond to manure applications due to symbiotic N_2 fixation in legumes; however, manure and compost applications have been shown to increase CP in mixed forage stands (Min et al., 2002).

Alfalfa ash contents were 7 g kg^{-1} lower in urea and SUPERU relative to all other treatments on average, this observation was reflected by the fertilizer vs. manure, and urea vs. compost and manure contrasts. Otherwise, contrasts suggested there were no significant differences between the fertilization strategies on alfalfa ADF, NDF, CP, CF, lignin, starch, and NEL. The relatively higher alfalfa ash content where manure was applied may be related to elevated alfalfa tissue K contents observed where manure was applied. Further regression analysis indicated a significant positive correlation between alfalfa ash and tissue K contents ($P < .001$, $r^2 = .30$, data not shown). Higher ash content should coincide with a drop in nonfiber carbohydrates and consequently TDN. Relative to spring and fall manure, mean alfalfa TDN was 10 g kg^{-1} higher under synthetic fertilization however considered insignificant by contrast testing ($P = .126$).

4 | CONCLUSIONS

Increased use of manure products in southern Idaho warranted exploration into impacts on soil nutrient stocks, tissue nutrient contents and removal, and forage quality. This study suggested that application of manure and manure products has a considerable effect on these properties at typical regional application rates (56 and 33 Mg ha^{-1}). Testing for manure P content and tailoring application rates will be beneficial for avoiding limitations of P-based manure management. Malting barley producers should increase oversite when nutrient requirements are being addressed through manure products to avoid losses in extract quality arising from increased protein content. Similarly, alfalfa rotations entering a field with a history of organic application should have forages tested for K so that rations can be tailored to circumvent hypomagnesemia (tetany) incidence. Both manure and composted manure application increased crop nutrient concentration and removal of macronutrients which suggests their consideration in prescribing drawdown and future application rates. The current Idaho N, P_2O_5, and K_2O removal estimates were holistically representative of all fertilized treatments except in spring malting barley, in which N removal was overestimated by 28%. However, contrast testing supported the use of separate nutrient removal estimates or the implementation of adjustment factors for production systems using organic amendments. There was no evidence to support alteration of nutrient removal estimates due to SUPERU use or between fall and spring applications of manure. Adjustments to current Idaho N, P_2O_5, and K_2O were not consistent among crop or nutrient. Recommendations for revising Idaho N, P_2O_5, and K_2O removal estimates and implementation of organic amendment adjustment factors have been provided.

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AUTHOR CONTRIBUTIONS

A. Bierer: Formal analysis; Investigation; Visualization; Writing – original draft; Writing – review & editing. R. S. Dungan: Conceptualization; Data curation; Investigation; Project administration; Writing – review & editing. D. D. Tarkalson: Conceptualization; Data curation; Investigation; Methodology; Project administration; Writing – review & editing. A. B. Leytem; Conceptualization; Data curation; Formal analysis; Investigation; Methodology; Project administration; Supervision; Writing & original draft; Writing – review & editing.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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