Received: 27 February 2025 | Accepted: 14 August 2025

DOI: 10.1002/agj2.70177

Agronomy Journal

ORIGINAL ARTICLE

Agronomy, Soils, and Environmental Quality

Management practices that maximize alfalfa forage harvested on farms: Insights from technological groups

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Assigned to Associate Editor Lisa Baxter.

Funding information
U.S. Alfalfa Farmer Research Initiative of the National Alfalfa & Forage Alliance; Midwest Forage Association; AFRI Sustainable Agricultural Systems Coordinated Agricultural Project (SAS-CAP), Grant/Award Number: 2021-68012-35917; USDA; National Institute of Food and Agriculture

Abstract

Alfalfa (*Medicago sativa* L.) is essential for the US livestock industry and provides critical ecosystem services. However, a 30%–50% gap in forage harvested persists between farmers and research fields. This study surveyed 24 farmers in the US Midwest managing 38 alfalfa fields to identify practices that maximize forage harvested. Most fields were seeded in spring under vertical tillage, primarily for haylage. Fields with more than three cuts and those harvested for haylage or silage showed greater forage harvested (yield). Previous crop, type of tillage, interval between cuts, organic management, forage use, manure, sulfur (S), and potassium (K) application in the seeding year were associated with alfalfa forage harvested. Inputs in the established stand, including herbicide, boron (B), and S, further influenced productivity. Conditional inference tree analysis revealed three technological groups based on alfalfa forage harvested and management. Group 1 achieved the greatest forage harvested based on more nutrient inputs, like S, and more than three cuts for haylage and silage. Group 2 had lower forage harvested, relying more on manure than fertilizers, and with similar cutting frequency. Group 3 had the lowest forage harvested, using alfalfa for hay with fewer inputs and longer cutting intervals. Despite a relatively small sample size, these findings emphasize the importance of integrated management strategies in achieving greater alfalfa forage harvested and closing the productivity gap.

Plain Language Summary

Alfalfa is an important forage for livestock and the environment, but there is a large difference between the yields in research fields and the commercial farms. We asked 24 farmers in the US Midwest about their management practices and alfalfa yields. Most farmers planted in spring under vertical tillage, primarily for haylage. Fields

Abbreviations: ADF, acid detergent fiber; ANOVA, analysis of variance; CP, crude protein; DDM, digestibility of dry matter; DMD, digestible dry matter; DMI, dry matter intake; NDF, neutral detergent fiber; RFV, relative feed value.

with more than three cuts and those harvested for haylage or silage showed greater yield. We identified three technological groups based on alfalfa forage yield and management. Group 1 had the highest yields based on more nutrient inputs and more than three cuts for haylage and silage. Group 2 had lower yields, relying more on manure than fertilizers, and with similar cutting frequency. Group 3 had the lowest yields, using alfalfa for hay with fewer inputs and longer cutting intervals. These findings emphasize the importance of integrated management strategies in achieving greater alfalfa forage and closing the productivity gap.

1 | INTRODUCTION

Alfalfa (*Medicago sativa* L.) is the fourth largest crop in the United States in terms of both area and production value (Fernandez et al., 2019; USDA-NASS, 2022) and plays a major role in sustaining the dairy industry in the US Midwest (Osterholz et al., 2019). Its economic and ecological contributions are also substantial, fostering sustainable farming practices through its perennial root system, dense canopy of leaves providing effective ground cover, and capacity to fix nitrogen (N) (D. Putnam et al., 2001). Alfalfa is also valued for its excellent nutritive value, characterized by high crude protein (CP) concentration and digestibility, making it a preferred choice for dairy and beef production (Ball et al., 2001; Lorenzo et al., 2020; D. Putnam et al., 2001). Furthermore, alfalfa is a resilient crop in the face of climate change with high resistance to drought (Picasso et al., 2019).

Despite improvements in alfalfa breeding and agronomic management practices, average alfalfa forage harvested (i.e., yield) on farms remains significantly lower—by 30%–50%—of the potential established by research trials and high-performing farms where forage harvested can exceed 13 Mg ha^{-1} in rainfed alfalfa in the US Midwest (Baral et al., 2022; Russelle, 2013). Closing this disparity between possible and actual on-farm alfalfa production has the potential to enhance farm profitability (Undersander, 2001).

An increase in alfalfa production and resource use efficiency could be achieved by a better understanding of common management practices associated with greater alfalfa forage harvested. Similarly, recognizing key differences among alfalfa farms can inform a range of best management practices. For instance, fertility management is essential for maximizing forage harvested, with sulfur (S) fertilization proven to enhance alfalfa forage harvested and improve nutritional value by increasing CP content and reducing acid detergent fiber (ADF) (Undersander et al., 2011; Wan et al., 2022). However, there is limited published research on the specific management practices that maximize alfalfa forage harvested on commercial US Midwest farms.

To address this gap, we conducted a multiyear on-farm study across 38 commercial alfalfa fields in the US Midwest, using farm surveys combined with descriptive statistics, linear models, and conditional inference trees to identify the management practices most strongly associated with greater forage harvested. This approach allowed us to account for field- and time-dependent variability and reveal meaningful patterns that could guide improved on-farm decisions. Additionally, by categorizing fields based on forage use (hay, haylage, and silage) and relative yield (high vs. low), we explored how specific combinations of practices relate to performance across different production goals.

The goals of this study were to (1) describe agronomic management practices common in alfalfa production in the US Midwest; (2) identify management practices associated with greater forage harvested on farms, specifically fertilization, pesticide application, and harvest management; and (3) identify groups of farms with management practices associated with either increased or decreased alfalfa forage production.

2 | MATERIALS AND METHODS

2.1 | Farmer selection and survey

During 2021 and 2022, alfalfa growers across the US Midwest were recruited for a detailed survey on management practices. We contacted farmers through county agents, extensionists, industry, and other farmers with printed flyers and emails. Information was received from 24 farmers (Figure 1) from Wisconsin (20), Illinois (3), and Michigan (1). These farmers provided data from 38 fields in different years, resulting in 66 field-by-year combinations.

An in-depth questionnaire on management practices was designed by the research team and completed by farmers (Figure S1). The survey form included field(s) area, soil information (soil type and analyses), age of alfalfa stands, crops before alfalfa establishment, use of cover crops, and tillage. In the alfalfa seeding year, information was gathered on planting date, seeding rate, alfalfa variety, presence of grasses in the seeding mix, row spacing, seeding depth, nutrient application, pest and disease management and incidence, and concerns with compaction. For fields under production, harvest information was requested (equipment, cutting height, and width) and, for each cut, harvest date, wet weight of forage harvested, dry matter (DM) concentration, stand assessment, and additional input applications. Farmers provided data on alfalfa forage yield (hereafter referred to as "forage harvested" following the guidelines from Allen et al. (2011) that had been measured and monitored using available on-farm forage harvested technology, such as weighted truck scales or digital technology from the chopper.

To estimate the nutrient input from chemical fertilizers, fertilizer types were noted, and the application rate was multiplied by nutrient concentration (Hannan, 2018). Phosphorus concentration was calculated as 0.44 times % P_2O_5. Potassium was 0.83 times % K_2O, 0.5 for KCl, and 0.44 for K_2SO_4 (C. A. M. Laboski et al., 2012). For gypsum (calcium sulfate, $CaSO_4$) concentration was 0.21 for calcium (Ca) and 0.17 for S (Sawyer, 2003). To estimate nutrient inputs from manure applications, average nutrient concentrations provided by two farmers were used. The nutrient concentrations utilized were as follows: 73 g kg $^{-1}$ for nitrogen (N), 45 g kg $^{-1}$ for phosphorus (P), 217 g kg $^{-1}$ for potassium (K), and 32 g kg $^{-1}$ for sulfur (S). For poultry litter, a concentration of 30 g kg $^{-1}$ N, 11 g kg $^{-1}$ P, and 15 g kg $^{-1}$ K were used. All the obtained results were subsequently converted into kg ha^{-1}.

Participating growers provided forage samples for nutritive value analysis. Samples of approximately 0.5 kg of fresh forage were collected by farmers at or near each cut, and then air-dried or oven-dried at a low temperature (≤60 –C) on farm. In total, 27 field samples were gathered and analyzed using near-infrared reflectance spectroscopy at the UW Madison Forage Lab, in the Department of Plant and Agroecosystem Sciences to estimate forage nutritive values (i.e., CP, neutral detergent fiber (NDF), and ADF). All forage samples were standardized before analysis by drying to constant weight, grinding to pass through a 1-mm screen, and analyzing them using the same instrument and calibration protocol. Based on these results, the relative feed value (RFV), an index that compares the nutritive value of forages to that of full-bloom alfalfa, was calculated. The RFV was obtained using the following formulas: digestible dry matter (DMD) calculated as DMD = 88.9 − (0.779 × %ADF). Dry matter intake (DMI), expressed as a percentage of body weight, was calculated as DMI = 120 ÷ %NDF. RFV is then determined by the equation RFV = (DMD × DMI) ÷ 1.29 (Jeranyama & Garcia, 2004).

Most farms provided information from only one field. In a few instances where two fields of the same farm were included, the management practices were consistent across fields. Soil order, texture class, and drainage class for each field were determined using the Web Soil Survey (Soil Survey Staff, n.d.) and are reported for the most predominant area in each field (Table S1).

Core Ideas

- Alfalfa farmers in the US Midwest were surveyed to identify management practices that maximize forage harvested.
- Three technological groups were identified based on alfalfa forage harvested, use, inputs, and harvest management.
- Group 1 had the greatest forage harvested, used primarily for haylage or silage, and applied more inputs.
- Group 2 had lower forage harvested than Group 1, mainly used for haylage, and applied less inorganic fertilizer.
- Group 3 had the lowest forage harvested, used mainly for hay, and applied minimal inputs.

2.2 | Statistical analysis

Univariate frequency tables were used to provide an overview of management practices and the proportion of fields utilizing each one. These practices included seeding date; organic management; previous crop; type of tillage; alfalfa use; date of last cut; presence of grass in the mix; and the application of herbicide, fungicide, insecticide, manure, Ca/gypsum, N, P, K, boron(B), and S. Applications were reported for both the seeding year (spring- and fall-seeded stands, referred to as the seeding year) and the first year of fully established stands (referred to as the established stand). Chi-square tests were then performed to evaluate the association among these practices.

To analyze the variability of forage harvested across fields, and the association between forage harvested and management practices, the dependent variable forage harvested was adjusted as follows. The unit of analysis was each alfalfa field, which included at least 2 years of data collection (between 2019 and 2022), and two stand ages (ranging from 1 to 4). To account for this temporal and spatial variability, a generalized least squares (GLS) model was applied, treating the field as a repeated measure and specifying an AR1 covariance structure. Fixed effects for field and age were included to estimate adjusted means that reflect underlying variation while improving comparability. These adjusted forage values were used in subsequent analysis of variance (ANOVA) models to examine the effect of each individual management practice (independent variables) on forage harvested (Pinheiro & Bates, 2024).

To analyze the number of forage cuts as dependent variable, given that it is not a continuous variable, a Poisson regression model was fitted with fixed effects for field and stand

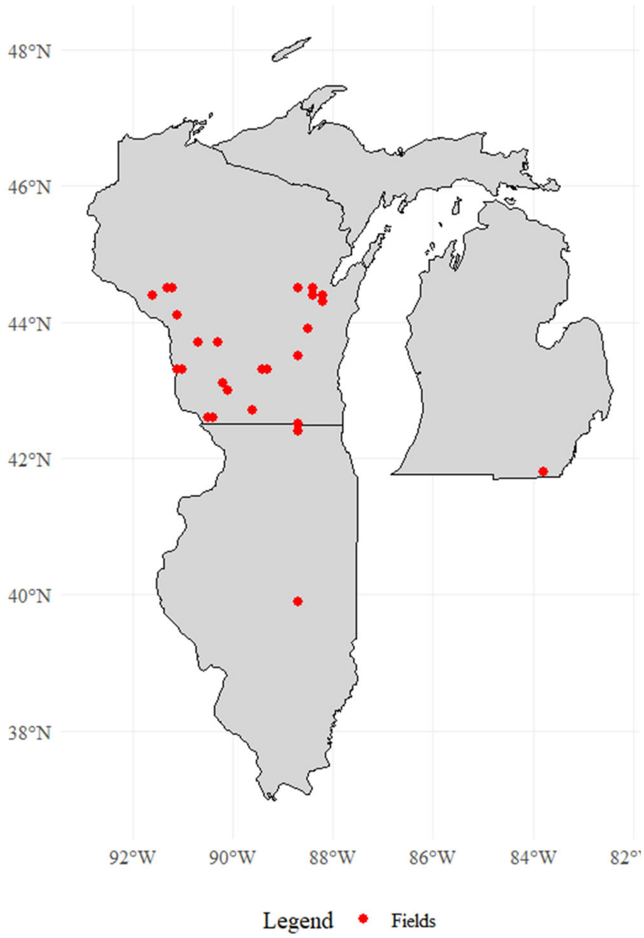

FIGURE 1 Location of alfalfa farmers who responded to the in-depth survey of alfalfa management practices in Wisconsin, Michigan, and Illinois.

age. This approach was selected to accommodate the discrete nature of the data (ranging from one to five cuts) and to adjust for structural differences across fields and ages, rather than relying on simple averages, which would not reflect variability in sampling. The adjusted means derived from the model were then used as predicted values in subsequent analyses to ensure consistency across field comparisons (Coxe et al., 2009).

To further explore the influence of multiple practices on forage harvested, a linear regression model was constructed using the "lm" function in R, with forage harvested as the dependent variable and all management practices as independent variables. Model selection using backward elimination with the Bayesian information criterion was applied to retain the most significant variables in the final model. Fungicide was excluded from the analysis as it was not utilized in any field during the seeding year and was applied to only one established stand.

The harvested forage was then categorized into six groups based on alfalfa use (hay, haylage, or silage) and relative productivity ("High" or "Low," depending on whether the forage harvested was above or below the average for each alfalfa use). These groups served as the response variable in subsequent ANOVA tests (for management practices as continuous variables) and chi-square tests (for management practices as categorical variables), enabling the assessment of how individual management practices were associated with differences in each group.

Finally, the party package in R was employed to construct conditional inference trees (Chamberlain Malone et al., 2023; Hothorn et al., 2015) with the significant predictors from the linear regression model to identify the principal factors influencing the forage harvested as the response variable. The resulting three nodes allowed us to categorize fields into three distinct groups for the comparative assessment of management practices. To investigate the associations and frequencies of each categorical variable across the different forage harvested groups, chi-square tests and contingency tables were utilized. For the continuous variables (forage harvested, RFV, cuts, interval between cuts, and total nutrients), ANOVA was used to identify the impact of these variables on the three groups. All effects were evaluated for statistical significance at $\alpha = 0.05$. However, for forage nutritive value variables, a 10% significance level ($\alpha = 0.10$) was applied due to their high natural variability, which can reduce statistical power and mask potentially important effects when using a stricter threshold. Data analysis was performed with the R software (R Core Team, 2024).

3 | RESULTS

3.1 | Establishment practices

The survey revealed a diverse range of management practices adopted by farmers across fields (Figure S2). Corn (*Zea mays* L.) was the most prevalent crop (66%) before alfalfa, followed by small grains including wheat (*Triticum aestivum* L.) and oats (*Avena sativa* L.) (16%), and finally soybean (*Glycine max* L., 10%). Thirty-four percent of the fields employed conventional tillage, 50% utilized vertical tillage, and 16% practiced no-tillage. Compaction problems were reported by only 5% of farmers with no-till and 3% of farmers with conventional tillage, and none of the farmers implemented traffic control. Seventy-four percent of the stands were planted in the spring (April–May), and 16% were certified organic fields.

Fifty-three percent of the fields used seeding rates between 19 and 28 kg ha^{-1}, while 47% used seeding rates of 15–17 kg ha^{-1}. Forty-five percent of the fields included alfalfa mixed with grass, such as oats or fescue (*Schedonorus arundinaceus* (Schreb.)). All farmers utilized the same row spacing (between 18 and 19 cm), likely due to the use of similar equipment. The target depth for seeding was between 0.6 and 1.3 cm for 85% of the fields, while only 10% had greater depths, between 1.3 and 2.5 cm. Similarly, cutting height (5–8 cm) and width (7.6–11 m) were uniform among fields.

Climatic conditions during the growing season (April–October) were generally favorable across sites, but some local variability was present. To reflect this, we report average monthly temperatures and precipitation using data from the closest weather stations to the farms (Tables S8 and S9). During this period, the monthly average temperature was 16 ˚C, with a mean minimum of 7 ˚C and a mean maximum of 22 ˚C. Average monthly precipitation was 81 mm, ranging from a minimum of 30 mm in April 2021 (across all fields) to a maximum of 142 mm. While these values provide a reasonable approximation, we acknowledge they may not fully capture microclimatic variability or farm-specific conditions.

3.2 | Inputs

Weed control with herbicides decreased from 53% in the seeding year to 11% in the established stands. Roundup ready varieties were utilized in 48% of the fields, while the remaining varieties were predominantly conventional (46%), followed by organic (5%) (Table S2).

Strong associations were found using chi-square (Figure S3) among herbicide applications (Table S3) in the seeding year and alfalfa use ($p < 0.01$), tillage method ($p = 0.03$), the use of alfalfa mixed with other grasses ($p = 0.02$), insecticide application ($p = 0.02$), and manure application ($p = 0.01$) in the first year. In fields where weed control was implemented with herbicide in the seeding year (47% of fields), alfalfa fields were used for haylage (70%) or silage (30%), employing more conservative soil management practices (65% under vertical tillage), and only 25% incorporated grasses in their alfalfa stands. Other inputs such as insecticide and manure application occurred in 65% and 85% of seeding year fields under herbicide treatment.

Conversely, the absence of herbicide use in the seeding year was strongly associated with alfalfa used as hay (72%) and was often complemented by the incorporation of mixed grass (67%) and conventional tillage (56%). Among these fields, 38% were organic, and they generally showed a reduced tendency to apply inputs such as insecticides.

Only in 4% of the fields *Phytophthora* sp. was reported, but only at low incidence or under wet conditions; most farmers did not report any disease-related problems. Fungicide application occurred in 3% of fields and only in established stands. However, 45% of fields received insecticide for weevil (*Hypera postica*) or potato leafhoppers (*Empoasca fabae*) in their seeding year and 37% in established stands.

Fifty percent of farmers reported using soil testing. Among them, 71% conducted tests every 2–4 years, while the remaining 29% either tested less frequently (every 7–10 years) or did not report the frequency. Only 20% of these farmers shared their soil test data. However, despite all of them having elevated soil K levels, 75% still applied K fertilizer, and 50% applied manure during the seeding year. Additionally, 50% also apply K in established stands. In contrast, P fertilizer was used by only one farmer during the seeding year, and none applied it to established stands.

In the seeding year, 63% of fields received manure and chemical fertilizers with K (58%), B (39%), and S (47%). However, in established stands, manure applications dropped to only 11% and K from chemical fertilizers increased to 76% of fields, while chemical fertilizer applications of B and S also increased to 66% of fields. Of the fields that received manure, 84% used liquid dairy manure, with an average application rate of 131,000 ± 42,900 L ha $^{-1}$. Solid dairy manure was applied in 8% of fields at an average rate of 44.8 ± 2.2 Mg ha $^{-1}$, while chicken litter was used in 8% of fields at a rate of 5.6 ± 2.2 Mg ha $^{-1}$. Regarding application timing, 84% of fields received manure before seeding, while 16% employed manure both before seeding and during the growing season.

To determine the sources of applied nutrients in fields where they were employed, their contributions from either manure or chemical fertilizers were estimated. In the seeding year, manure was the primary source of key nutrients such as N, P, K, and S. On average, manure provided 115 ± 33 kg ha^{-1} of N, 72 ± 24 kg ha^{-1} of P, 330 ± 126 kg ha^{-1} of K, and 53 ± 14 kg ha^{-1} of S. In contrast, chemical fertilizers provided lower quantities, averaging 11 ± 5 kg ha^{-1} of N, 13 ± 4 kg ha^{-1} of P, 143 ± 79 kg ha^{-1} of K, and 25 ± 7 kg ha^{-1} of S. In established stands manure applications were lower, while contributions from chemical fertilizers remained similar. N and P levels were low in the established stands and primarily came from manure applications (Figure S4).

Important associations were found among all the nutrients applied (Figure S3). Sulfur applied in the seeding year demonstrated the highest association with other nutrients (Table S4), including N, P, K, B, and Ca ($p < 0.01$) in the same season. Additionally, there was an association with the application of S in both the seeding year and established stand ($p < 0.01$). In the seeding year, 47% of fields received S, with 50% of them also receiving N, 56% P, 94% K, 78% B, and 56% Ca. In established stands, 89% of fields also received S. Conversely, fields that did not receive S did not receive other nutrients either ($p < 0.01$).

3.3 | Alfalfa forage use and harvest management

Management strategies across fields were strongly influenced by the intended use of alfalfa forage. These categories were defined as hay (15%–20% moisture), haylage (40%–60% moisture), or silage (60%–70% moisture), based on the typical moisture content at harvest. Fifty percent of the fields used

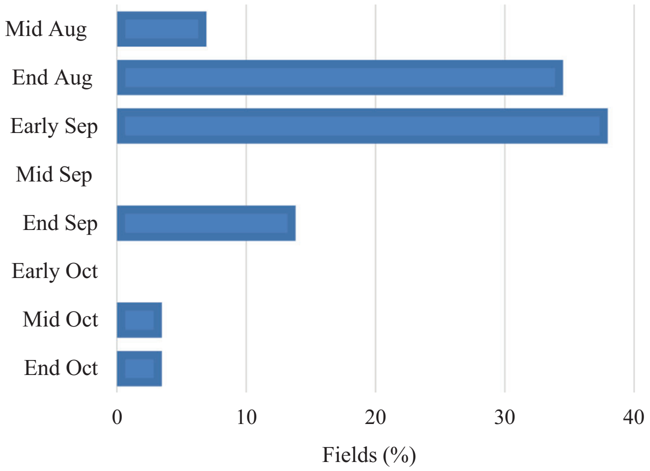

FIGURE 2 Percent of alfalfa fields according to the date of the last cut for 38 alfalfa fields surveyed in the US Midwest.

alfalfa primarily for haylage, 34% for hay, and the remaining fields (16%) for silage (Figure S2). These distinct end use shaped decisions, such as cutting frequency and input use. Haylage and silage production were mainly associated with more than three cuts (Figure S3; Table S5). In contrast, 70% of fields with three or fewer cuts harvested hay.

Nutrient and pesticide input levels were also closely aligned with forage use. Input utilization was higher in haylage and silage fields, especially during the seeding year (Table S5). The intervals between cuts were measured by counting the days between consecutive cuts, from the first to the fifth. The results showed that over half of the fields had 25–35 days of cutting intervals (Figure S2).

For the analysis of the timing of the last cut, each month was divided into three periods of 10 days. Seventy-two percent of the fields completed their final cut in late August or early September, with 14% finishing by the end of September. Only 6% of the fields were harvested for the final time in October (Figures 2–4).

Strong associations were observed between the timing of the last cut and several factors (Figure S3) including the interval between cuts ($p < 0.01$); the end use of alfalfa ($p = 0.05$); organic fields ($p < 0.01$); and herbicide ($p = 0.03$), Ca ($p = 0.03$), B ($p = 0.01$), and S ($p < 0.01$) application in the seeding year. In established stands, associations were also observed between the timing of the last cut, manure application ($p = 0.02$), and B application ($p = 0.05$).

Among the fields that had their final cut between late August and early September, 43% were harvested for haylage and 57% received herbicide applications, 48% received B and S during the seeding year, and 71% received additional B applications as established stands (Table S6). In contrast, 20% of the fields with their last cut at the end of September or later were more frequently harvested for hay (67%), with 50% receiving S during the seeding year, and 67% were managed organic.

3.4 | Forage harvested

Forage harvested was highly variable among fields and stand ages, ranging from ~1.1 Mg ha^{-1} for hay in the seeding year to 17.3 Mg ha^{-1} in established stands for haylage. Stand age had a significant effect on forage harvested ($p < 0.01$), with the highest values observed in second-year stands (11.6 ± 2.4 Mg ha^{-1}). These were not significantly different from third (10.2 ± 2.8 Mg ha^{-1}) or fourth-year stands (10.5 ± 3.6 Mg ha^{-1}), while the seeding year had significantly lower forage harvested (4.0 ± 1.8 Mg ha^{-1}) compared to all other ages. The overall average DM concentration for the season was approximately 42%.

Seasonal forage harvested was affected by the interval between cuts ($p < 0.01$) and end use ($p = 0.01$). Longer intervals between cuts (greater than 50 days) resulted in lower forage harvested, with an average of 4.2 ± 1.0 Mg ha^{-1}, which was lower than the forage harvested from intervals of 25 to 50 days (9.6 ± 0.9 Mg ha^{-1}). Additionally, harvesting alfalfa for haylage (9.5 ± 0.6 Mg ha^{-1}) and silage (10.8 ± 1.0 Mg ha^{-1}) resulted in greater productivity compared to harvesting for hay (7.2 ± 0.7 Mg ha^{-1}).

In the seeding year, manure application ($p = 0.05$) and herbicide use ($p = 0.02$) were associated with a 23% and 26% increase in forage harvested, respectively. In contrast, in established stands, fields receiving P inputs showed 30% lower forage production ($p = 0.02$) (Table S7).

When analyzing the combined effect of all variables on forage harvested, our linear model included only the variables selected through backward elimination to identify the management practices that had the most significant influence. The results showed that nonorganic fields produced 31% higher forage than organic fields ($p < 0.01$). Having corn as the previous crop led to a 25% increase in forage harvested compared to soybeans or small grains ($p < 0.01$). Conventional tillage resulted in a 19% higher forage harvested than vertical and no-till, which showed similar effects ($p = 0.01$). A cutting interval of less than 50 days ($p < 0.01$), alfalfa use for haylage or silage ($p < 0.01$), and manure application in the seeding year ($p = 0.04$) were also associated with higher forage harvested.

Regarding nutrient fertilization, K ($p < 0.01$) and S ($p < 0.01$) in the seeding year increased forage harvested by 35% compared to no application. In established stands, the absence of herbicide use ($p = 0.04$) or B application ($p = 0.02$) resulted in 20% higher forage harvested, while S application increased forage harvested by 24% ($p < 0.01$) compared to no application. However, these management practices were strongly associated, suggesting they were often implemented together.

Due to the strong influence of alfalfa use on forage harvested, fields were categorized into six groups based on their type of alfalfa use (hay, haylage, or silage) and whether the amount of forage harvested was below (low) or above (high)

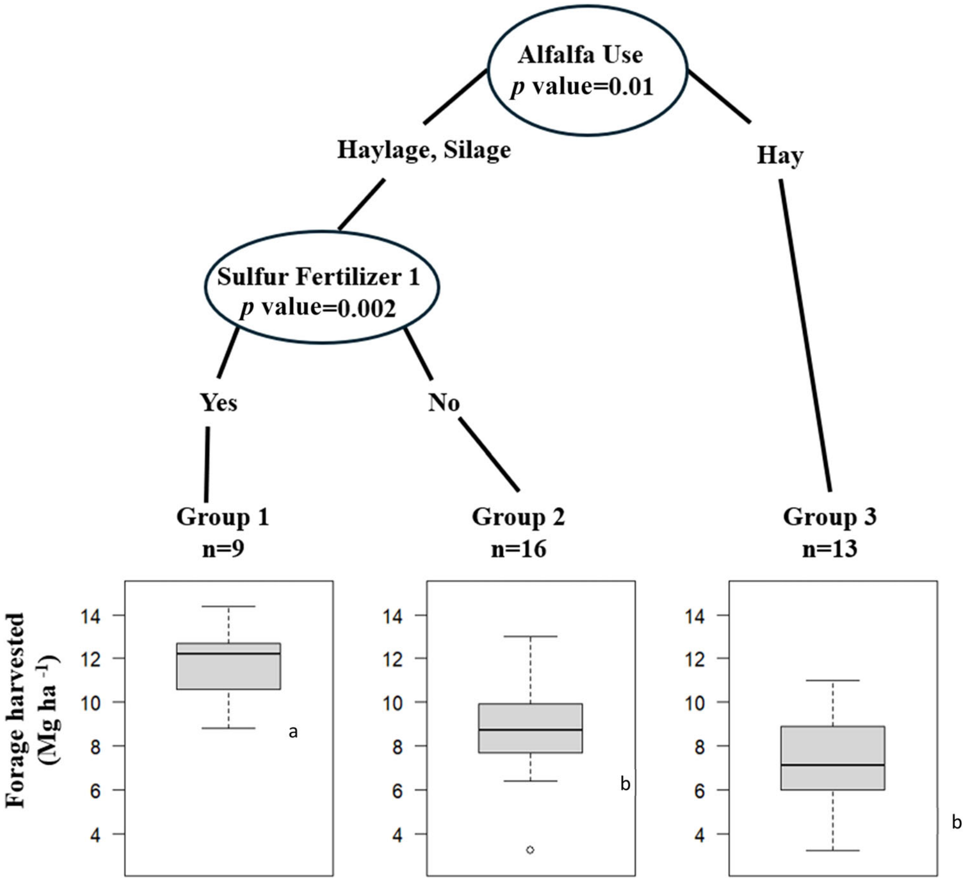

FIGURE 3 Conditional inference tree analysis of forage harvested (Mg ha^{-1}) with significant management practices from the linear model resulted in three technological groups for 38 alfalfa fields surveyed in the US Midwest. Distribution of alfalfa forage harvested (yield) for each group: the gray rectangle represents the range from the first to the third quartile, the dark line in the middle indicates the median, and the whiskers represent the minimum and maximum values within the data for each group. Means with different letters are different at $\alpha = 0.05$.

the average for that use group. Based on this, the group names were defined as follows: hay–low, hay–high, haylage–low, haylage–high, silage–low, and silage–high.

Results showed that both silage groups generally had slightly higher forage harvested overall (Table 1), although not significantly different from the haylage high group. In the silage high group, N and P fertilization did not appear to contribute to increased forage harvested, and P application in the second year also showed no clear effect. This pattern suggests that, within this dataset, higher forage production for silage was not associated with greater N or P fertilization. Organic management was associated with greater forage harvested in the hay groups, and grass mixtures consistently contributed to greater forage harvested across all high-performing groups (hay high, haylage high, and silage high). In both hay groups, higher nutrient inputs were linked to increased forage harvested, whereas in both silage groups, nutrient inputs had a limited impact. Soil testing was more commonly reported in the high forage harvested groups within the hay and haylage groups, but this pattern was not observed in the silage high group.

3.5 | Alfalfa technological groups

The conditional inference tree analysis identified only the interval between cuts as the most influential factor ($p < 0.01$), with intervals exceeding 38 days resulting in lower forage harvested. However, this variable was highly associated with other management practices, potentially hindering the identification of distinct groups. To address this, the analysis was repeated, excluding this variable. The results indicated that the end use of alfalfa and S fertilizer application during the seeding year were the most influential factors in determining the productivity of the stands (Figure 3).

The fields were then categorized based on the groups generated by the conditional inference tree and used a chi-square analysis to examine the management practices associated with each group (Table 2). All fields in Group 2 and 78% in Group 1 had more than three cuts per year, showing that a more frequent cutting regimen contributed to overall greater forage harvested (Table 2). Additionally, these groups primarily utilized alfalfa stands for haylage and silage. In contrast, fields in Group 3 were exclusively harvested for hay, and associated

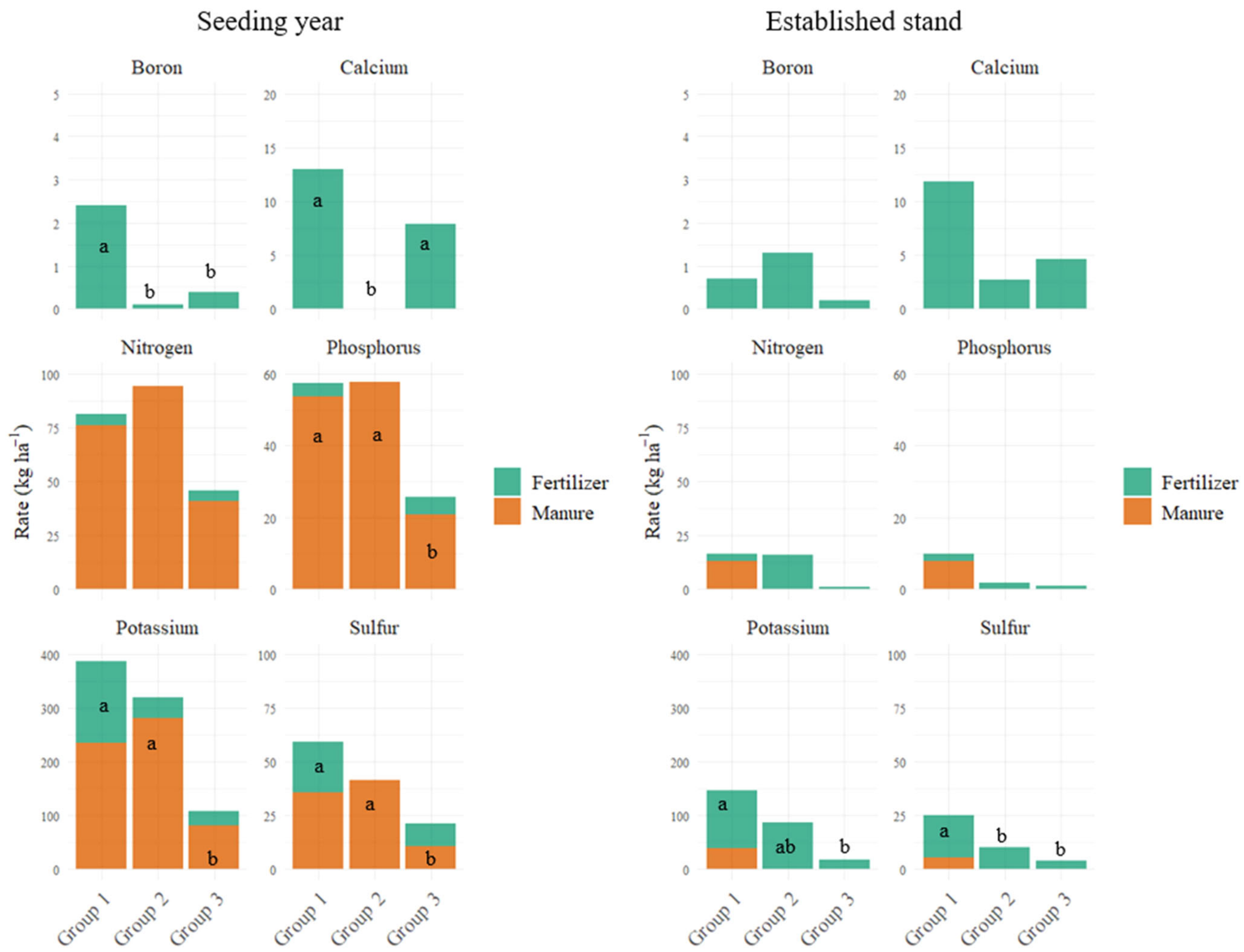

FIGURE 4 Total nutrients from fertilizer and manure (kg ha $^{-1}$) application per technological group ("High-input silage and haylage" [Group 1], "Medium input haylage" [Group 2], and "Hay fields" [Group 3]) of 38 alfalfa fields in the US Midwest for seeding year and established stand. Means among groups within each nutrient with different letters are different at $\alpha = 0.05$.

with lower forage harvested (Table 2). A substantial majority of fields in Group 1 received a wide range of inputs in the first year, including herbicides (78%), manure (89%), and various fertilizers such as Ca (56%), N (44%), P (33%), K (89%), B (89%), and S (100%; Table 2; Figure 4). In contrast, fields in Group 2 also received herbicides (81%), but the fertilization strategy relied more on manure (75%) than on inorganic fertilizers (Table 2; Figure 4). Fields in Group 3 received a moderate selection of inputs, manure, and a few types of fertilizers, with no application of herbicides (Table 2; Figure 4). Therefore, based on these analyses, the three technological groups were named "High-input silage and haylage" (Group 1), "Medium input haylage" (Group 2), and "Hay fields" (Group 3).

The timing of the last cut differed across groups, reflecting distinct management strategies. In Groups 1 and 2, most fields completed their final cut in August or early September, whereas fields in Group 3 typically had their last cut in early or late September. This variation is likely linked to the cutting intervals, as most fields in Groups 1 and 2 had intervals between 25 and 35 days, while those in Group 3 followed longer intervals, often exceeding 40 days (Table 2).

In established stands, all fields in Group 1 were fertilized with K and S. A larger proportion of fields from Group 2 also received K and S fertilization, but at lower rates than Group 1 (Figure 4). In contrast, herbicide application decreased across Groups 1 and 2 in established stands (Table 2).

In this study, cutting strategies were compared with harvest management categories described by Undersander et al. (2011), which outline three typical cutting schedules depending on grower objectives (Figure 5), maximizing stand persistence ("Persistence"; longer intervals between cuts), prioritizing forage quality or nutritional value ("Quality"; shorter, more frequent cuts early in the season), or balancing high nutritional value and greater forage harvested ("Yield & Quality"). Fields in Group 3 presented more variability and seemed to follow a persistence-focused schedule, with an average of 46 days between cuts. However, when there were

TABLE 1 Percentage of fields in each management practice associated with each alfalfa use group (hay–low, hay–high, haylage–how, haylage–high, silage–low, and silage–high) for 38 alfalfa fields surveyed in the US Midwest.

	Alfalfa use						
	Hay		Haylage		Silage		
Group	Low	High	Low	High	Low	High	*p* value
Number of fields	7	6	11	8	3	3	
Soil test (% fields)	14	33	45	75	100	67	ns
Forage harvested (Mg ha^{-1})	5.3d	9.3b	7.7c	12a	9.9ab	11.6a	<0.01
	% fields						
Cuts							ns
≤3	71	67	0	0	33	33	
>3	29	33	100	100	67	67	
Last cut							ns
August	0	20	75	60	33	50	
September	100	80	13	20	67	50	
October	0	0	13	0	0	0	
Interval cuts (days)	50a	40b	3 b	31b	30b	30b	<0.01
	% fields						
≤35	29	40	88	80	100	100	
>35	71	60	12	20	0	0	
Grass mix	29*	100*	18	50	33	67	0.03
Previous crop							ns
Corn	57	67	64	100	33	33	
Soybean	0	17	9	0	67	0	
Other	43	17	27	0	0	67	
Tillage							ns
No tillage	14	17	9	25	0	33	
Vertical	29	33	64	50	100	33	
Conventional	57	50	27	25	0	33	
Seeding date							ns
Fall	43	0	36	13	0	67	
Spring	57	100	64	88	100	33	
Organic	29	50	0	13	0	0	ns
Seeding year							
Manure application	14	50	82	75	100	67	0.04
Chemical fertilizer							
Calcium	29	50	0	38	0	67	ns
Nitrogen	29	50	0	13	100*	0*	<0.01
Phosphorus	57	50	0	0	100*	0*	<0.01
Potassium	71	67	27	63	100	67	ns
Boron	43	50	0*	50*	100	67	0.02
Sulfur	71	67	0*	50*	100	67	0.01
Weed and pest management							
Herbicide	0	0	73	75	100	100	ns
Insecticide	14	50	36	38	100	100	ns
Established stand							
Manure application	14	17	0	25	0	0	ns
Chemical fertilizer							

(Continues)

TABLE 1 (Continued)

Group	Alfalfa use: Hay Low	Hay High	Haylage Low	Haylage High	Silage Low	Silage High	*p* value
Calcium	14	33	36	38	0	67	ns
Nitrogen	14	17	27	25	67	0	ns
Phosphorus	43	0	9	0	67*	0*	0.02
Potassium	43	67	82	100	100	67	ns
Boron	57	67	64	63	100	67	ns
Sulfur	43	83	64	63	100	67	ns
Weed and pest management							
Herbicide	0	0	36	0	0	0	ns
Insecticide	29	33	18	50	67	67	ns

Note: Different letters in the same row indicate significant differences at $\alpha = 0.05$.
Abbreviation: ns, not significant.
*indicates significant differences between low and high alfalfa use groups ($\alpha = 0.05$).

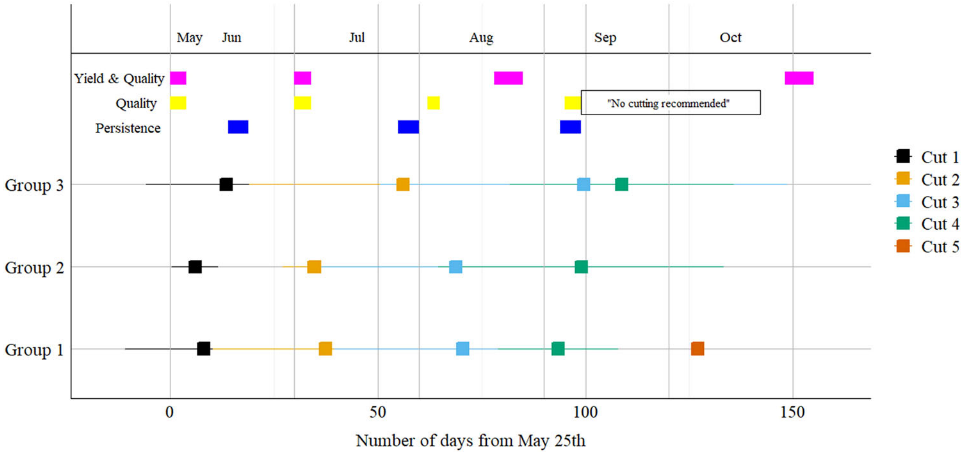

FIGURE 5 Distribution of alfalfa harvest schedules across five cuts, showing mean harvest dates and standard deviations for each cut, grouped by the three technological groups (“High-input silage and haylage” [Group 1], “Medium input haylage” [Group 2], and “Hay fields” [Group 3]) of fields identified in this study (shown on the *y*-axis). Colored squares indicate the average cutting date for each group and cut, with horizontal lines representing ± 1 standard deviation. Cut numbers are differentiated by square color: black (Cut 1), orange (Cut 2), cyan (Cut 3), green (Cut 4), and brown (Cut 5). For comparison, the recommended harvest schedules for three different goals from Undersander et al. (2011) are presented in the top rows: magenta represents “Yield & Quality,” yellow represents “Quality,” and blue represents “Persistence.” The note “No cutting recommended” refers to a recommended rest period.

more than three cuts (about 30% of cases), the final cut fell in a period less ideal for persistence (Figure 5). In contrast, Groups 1 and 2 appeared to center on maximizing forage harvested and nutritional value in the first two cuts, averaging 30 days between cuts, while the last two cuts seemed to focus more on the nutritional value of the stands (Figure 5). Additionally, Group 1 made a fifth cut in early October, which may have contributed to their greater forage harvested relative to the other groups, despite being outside the recommended cutting period.

Forage nutritional value varied among the groups (Table 3), reflecting the effects of harvest timing and plant maturity. Groups 1 and 2 began with high CP and DDM (digestibility of dry matter) levels in Cut 1, which gradually decreased by Cut 4, though these differences were not significant. Conversely, Group 3 had the lowest initial CP and DDM content in Cut 1 but experienced an increase by Cut 4. Fiber components, including ADF and NDF, generally increased in later cuts for Groups 1 and 2, again without significant differences. In contrast, Group 3 showed a decline in both ADF and NDF by Cut 4, suggesting improved digestibility. RFV also varied, with Groups 1 and 2 averaging RFV values of 143 and 142, respectively, while Group 3 averaged 134, though these differences were not statistically significant (Table 3).

TABLE 2 Percentage of fields in each management practice associated with each technological group (“High-input silage and haylage” [Group 1], “Medium input haylage” [Group 2], and “Hay fields” [Group 3]) for 38 alfalfa fields surveyed in the US Midwest.

	Group 1 High input silage and haylage	Group 2 Medium input haylage	Group 3 Hay fields	*p value*
Number of fields	9	16	13	
Forage harvested (Mg ha^{-1})	12a	9b	7b	<0.01
Cuts (number)	4a	4a	3b	0.02
	% fields			
≤3	22	0	69	
>3	78	100	31	
Alfalfa use				<0.01
Hay	0	0	100	
Haylage	44	94	0	
Silage	56	6	0	
Last cut				<0.01
Mid August	25	0	0	
End August	13	80	9	
Early September	50	10	55	
End September	0	0	36	
Mid October	0	10	0	
End October	13	0	0	
Interval cuts (days)	30a	31a	46b	0.02
	% fields			
25–30	63	60	8	
31–35	25	30	25	
35–40	12	10	0	
40–50	0	0	34	
50+	0	0	33	
Organic	0	6	38	0.02
Seeding year				
Manure application	89a	75a	31b	0.01
Chemical fertilizer				
Calcium	56a	0b	38a	<0.01
Nitrogen	44a	0b	38a	0.01
Phosphorus	33a	0b	54a	<0.01
Potassium	89a	31b	69a	0.01
Boron	89a	6b	46a	<0.01
Sulfur	100a	0b	69a	<0.01
Weed and pest management				
Herbicide	78a	81a	0b	<0.01
Insecticide	78	38	31	ns
Established stand				
Manure application	22	0	15	ns
Chemical fertilizer				
Calcium	44	31	23	ns
Nitrogen	33	25	15	ns
Phosphorus	22	6	23	ns
Potassium	100a	81ab	54b	0.04
Boron	89	56	62	ns

(Continues)

TABLE 2 (Continued)

	Group 1 High input silage and haylage	Group 2 Medium input haylage	Group 3 Hay fields	*p value*
Sulfur	100a	50b	62ab	0.04
Weed and pest management				
Herbicide	0	25	0	0.05
Insecticide	67	25	31	ns

Note: Different letters in the same row indicate significant differences at $\alpha \leq 0.05$.
Abbreviation: ns, not significant.

TABLE 3 Average nutritional value of alfalfa forage sampled by cut and total for three technological groups ("High-input silage and haylage" [Group 1], "Medium input haylage" [Group 2], and "Hay fields" [Group 3]) of 38 alfalfa fields in the US Midwest.

		Forage harvested per cut	CP	ADF	NDF	OM	DDM	RFV
		Mg ha $^{-1}$	% of DM					
Group 1								
	Cut 1	4.1a	24	30b	37	89	65a	165
	Cut 2	3.3ab	22	36ab	44	85	61ab	135
	Cut 3	3.1b	20	38a	47	87	60b	121
	Cut 4	2.5b	22	34ab	42	89	63ab	145
	p value	0.02	0.12	0.08	0.27	0.6	0.08	0.14
Group 2								
	Cut 1	3.9a	21	32	42	90	64	148
	Cut 2	2.8b	21	34	43	88	62	146
	Cut 3	2.5cb	20	35	44	87	62	141
	Cut 4	1.9c	20	36	45	88	61	134
	p value	<0.01	0.99	0.75	0.95	0.7	0.75	0.9
Group 3								
	Cut 1	2.8a	15b	37a	50a	91	60b	113b
	Cut 2	2.2ab	19a	36a	44ab	90	61b	135b
	Cut 3	1.8b	19a	36a	46a	90	61b	130b
	Cut 4	1.7b	23a	30b	36b	89	66a	177a
	p value	0.07	0.01	0.07	0.04	0.33	0.07	0.03
Total								
	Group 1	1.5a	22a	34	42	88b	62	143
	Group 2	1.2a	20ab	34	44	88b	62	142
	Group 3	1.0b	19b	36	45	90a	61	134
	p value	<0.01	0.07	0.53	0.62	0.03	0.53	0.57

Note: Means for cuts or groups followed by different letters are different within the group at $\alpha = 0.10$.
Abbreviations: ADF, acid detergent fiber; CP, crude protein; DDM, digestibility of dry matter; DM, dry matter; NDF, neutral detergent fiber; OM, organic matter; RFV, relative feed value.

4 | DISCUSSION

4.1 | Alfalfa management practices and forage harvested

The survey findings revealed a varied range of management practices among farmers cultivating alfalfa in this study, with a significant portion choosing more conservationist approaches like vertical tillage and no-tillage. Tillage is a major contributor to soil erosion, leading to the loss of valuable topsoil, which contains essential plant nutrients and organic matter (Busari et al., 2015; Duiker & Myers, 2005). Additionally, eroded soil poses environmental risks by contaminating water bodies like streams, lakes, and estuaries (Duiker & Myers, 2005).

The intended purpose of the alfalfa crop strongly influenced management decisions. Hay fields, often organic, were harvested less frequently and used fewer inputs. In contrast, haylage and silage fields had more cuts and relied on higher input use to increase forage production and nutritional value. The intended use of alfalfa, whether for hay (15%–20% moisture), haylage (40%–60% moisture), or silage (60%–70% moisture), strongly influences management decisions, particularly in balancing the amount of forage harvested with its nutritional value. Haylage and silage systems offer advantages such as reduced leaf loss, lower risk of weather-related damage, and decreased field traffic compared to hay (Orloff & Mueller, 2008). Feeding haylage is particularly advantageous in hot conditions, offering a more palatable and digestible ration well-suited to total mixed rations. Haylage, due to its moderate moisture content and improved preservation, generally retains nutrients better and produces fewer undesirable fermentation products compared to high-moisture silage. While silage enables rapid harvest and greater forage accumulation, it can result in higher storage losses. These systems typically require more frequent harvests and greater use of inputs, including fertilizers and pest control, to maintain forage nutritional value. In contrast, hay systems prioritize DM and storage stability, often requiring fewer inputs. These distinctions emphasize how crop use shapes agronomic decisions and input intensity (Gordon et al., 1961; Kung et al., 2018; Orloff & Mueller, 2008; Sheaffer et al., 2000). The seeding date most preferred by the farmers was spring. In US Midwest states, farmers tend to prefer spring seeding over late summer seeding since it offers a better chance of achieving successful stand establishment (Undersander et al., 2011). Spring seeding with herbicides allows harvests in the same year, while late summer or fall seeding, after another crop harvest, typically offers high production in the following year (Fernandez et al., 2019).

Herbicide use declined in established stands, probably due to alfalfa's vigorous root system and dense canopy effectively competing with weeds for resources, and frequent mowing also helping deplete weed energy reserves. Furthermore, cutting before seeding in annual weeds reduces weed pressure, particularly advantageous for organic and herbicide-resistant weed control (Fernandez et al., 2019). Insecticide applications for weevils or potato leafhoppers were common. Although various insects such as aphids, weevils, and blister beetles can inflict damage, the potato leafhopper is often the most economically impactful pest affecting alfalfa across much of the United States (Bliss, 2023; Chasen et al., 2014).

Herbicide application during the seeding year was associated with the addition of manure in the same period. The main agronomic challenge associated with pre-seeding applications of manure is the stimulation of weed growth due to the introduction of additional weed seeds and/or manure, requiring management of the heightened weed pressure through herbicides or timely clipping (K. A. Kelling & Schmitt, 2011; Kunelius, 1974). Research has shown that although preplant manure application might initially exacerbate weed invasion in the seedling year, with adequate control, these problems typically dissipate after the first cutting (K. A. Kelling & Schmitt, 2011).

Herbicide during establishment was associated with conservationist tillage methods like no-tillage or vertical tillage, while fields intended for hay production were more likely to employ mixed grasses and conventional tillage, potentially serving as an alternative method for weed control. The use of grasses in the mix was associated with a reduction in herbicide use, highlighting how incorporating grasses as nurse crops can help manage weeds while reducing dependence on herbicides, a practice particularly appropriate to organic production systems (Fuerst et al., 2009). Additionally, the inclusion of grasses limits the range of herbicides that can be applied, particularly those targeting monocot species, which may also contribute to the observed reduction in herbicide use. Integrated weed management involves both active control methods, such as herbicides, cultivation, tillage, or biological agents, and passive strategies like cover crops or cultural practices, which indirectly affect weed growth (Klodd & VanGessel, 2019). As expected, organic fields were also more commonly associated with hay production and less likely to use inputs like insecticide or herbicide.

Efficient management practices, including fertilization, harvest strategies, and pest control, are key to improving alfalfa forage harvested and nutritional value (D. H. Putnam, 2021). Applying S, K, N, and P fertilizers could increase the forage harvested and CP content (Wan et al., 2022; Wei et al., 2024), while effective pest management further enhances forage harvested (Kanatas et al., 2021).

When soil pH levels are adequate, nutrient management plays a key role in increasing forage harvested, as this provides the necessary nutrients to support plant growth, (Undersander et al., 2011), and for replenishing nutrients removed during alfalfa harvests, where split applications are often recommended to prevent excessive nutrient uptake by the crop (Undersander, 2021). Nitrogen and P applications were low in established stands, likely because nodulated alfalfa plants fix N in a symbiotic relationship with rhizobium bacteria, thus reducing the need for N fertilization (Issah et al., 2020). However, incorporating small amounts of N may increase forage harvested, especially in sandy soils with low organic matter (K. Kelling, 2000; Undersander et al., 2011). Research conducted for 24 years by Fan et al. (2011) indicates that applying both inorganic fertilizers and organic manure to alfalfa can produce significant benefits in terms of forage harvested, stand longevity, and soil quality improvement. Also, K. A. Kelling and Schmitt (2011) observed a consistent trend across all locations in Minnesota and Wisconsin, indicating higher forage harvested in the initial full hay year when preplant manure was applied compared to untreated controls, and this effect may also extend into subsequent full production years. While comparable fertilizer treatments offered some advantages, particularly at sites with low soil testing values, the addition of manure led to significant increases in forage harvested (K. A. Kelling & Schmitt, 2003, 2011; Peters, 1991; Schmitt et al., 1993). However, repeated applications of manure at high rates may elevate forage K concentrations to unacceptable levels (K. A. Kelling & Schmitt, 2011).

Regarding the time of application, applying manure before seeding alfalfa is beneficial for optimizing nutrient availability, managing soil nitrate levels, and preventing crop damage. This practice supports better alfalfa establishment and growth while addressing environmental concerns related to nutrient runoff and soil health (Daliparthy et al., 1994; Darapuneni et al., 2024; Schmitt et al., 1993).

In this study, S and K fertilization in the seeding year and S in established stands increased forage yield compared to no application. Sulfur is crucial for alfalfa production in Wisconsin, especially in sandy or low-organic matter soils, as deficiencies can severely reduce productivity (C. A. M. Laboski et al., 2012). While adequate K levels enhance forage harvested through greater shoot mass (Berg et al., 2007), excessive K can reduce B uptake and digestibility, potentially lowering productivity (Heuschele et al., 2023).

These practices are often implemented together, emphasizing the need for soil testing to optimize nutrient management (C. A. Laboski, 2008; C. A. M. Laboski et al., 2012; Undersander et al., 2011). Soil testing is an important tool for guiding nutrient management decisions and enhancing input efficiency. However, only half of the farmers in this study reported using soil tests to adjust their nutrient management practices, and the use of soil testing varied among them. This inconsistency indicates differing levels of reliance on soil test data for informing nutrient management decisions.

The forage harvested observed in this study exceeded the 8.1 and 8.5 Mg ha^{-1} averages for hay and haylage, respectively, reported in the 2021 and 2022 USDA/NASS State Agriculture Overview for Wisconsin (USDA-National Agricultural Statistics Service Census of Agriculture, 2021, 2022). However, the results aligned closely with the 16-year on-farm established stand average of 9.8 Mg ha^{-1} for haylage reported by the Wisconsin Alfalfa Yield and Persistence Program (Bertram, 2021, 2022). While research trials are often conducted under optimal conditions with precise harvest timing, uniform nutrient availability, and equipment designed to minimize losses, our findings indicate that forage harvested from haylage and silage systems in established stands can reach levels closer to those achieved in research settings. In this study, haylage fields produced up to 17.3 Mg ha^{-1}, and average values across second- to fourth-year stands were above 10 Mg ha^{-1}. These outcomes align closely with the 13 Mg ha^{-1} reported in experimental trials under rainfed conditions in the US Midwest (Baral et al., 2022; Russelle, 2013). This suggests that, despite on-farm variability, intensive management systems such as haylage or silage may help reduce the gap between typical farm performance and the potential under ideal conditions.

The average DM concentration for the season was approximately 42%, slightly below the 44.5% average reported by the Wisconsin Alfalfa Yield and Persistence Program (2021, 2022). A clear trend of declining forage harvested DM from the first to the last cut was observed, accompanied by a simultaneous increase in DM concentration as cutting stages progressed. This pattern, also reported in other US Midwest studies (Wisconsin Alfalfa Yield and Persistence Program, 2021, 2022), is likely due to increased drying conditions and higher temperatures later in the growing season.

The number of cuts and the alfalfa use played a significant role in determining productivity in this study. Fewer cuts (<3) resulted in lower forage harvested, while haylage and silage production proved more productive than hay. Research conducted by Eckberg et al. (2022) showed that higher cutting frequencies resulted in increased forage harvested, improved nutritive value, and higher milk production per kilogram of alfalfa, without compromising stand persistence. This research suggests that in certain US Midwest environments, increasing cutting frequency may be advantageous for maximizing forage harvested and nutritive value in alfalfa (Eckberg et al., 2022).

4.2 | Alfalfa technological groups

The analysis identified the type of harvest and S fertilization in the seeding year as the most influential factors for discriminating fields with different forage harvested. Silage production was linked to higher S use, compared to hay production. Sulfur in these fields was often applied together with Ca, K, B, P, and N. Calcium was most commonly applied as calcium sulfate ($CaSO_4$), or gypsum, This practice likely contributed significantly to the S application levels observed, suggesting that S fertilization may be indicative of a more intensive nutrient management system, where a broader range of nutrients are carefully balanced to optimize forage harvested and nutritional value. These findings highlight the crucial role of nutrient application in determining alfalfa forage harvested. Proper establishment and initial growth of the alfalfa stand, which are crucial for forage harvested and nutritional value, are closely linked to accurate fertilization practices. Likewise, adequate soil fertility not only improves the ability to compete with weeds but also enhances its winter hardiness and stand persistence (Undersander et al., 2011).

The strategies for input use varied significantly across the groups. Group 1, focused on silage and haylage production, exhibited a high reliance on synthetic fertilizers and applied more herbicides and insecticides compared to the other groups, reflecting a higher level of chemical intervention to support their management goals. Group 2, which focused on haylage, primarily used manure as the nutrient source during the seeding year and used fewer insecticides than Group 1. Group 3, dedicated to hay production, used the fewest inputs overall, with no herbicides applied and minimal fertilizer use compared to Groups 1 and 2. This reflects a low-input management approach in comparison to the other groups. Fields in Group 1 and most in Group 2 primarily used alfalfa for haylage and silage and followed a frequent cutting schedule, resulting in greater forage harvested. In contrast, Group 3 fields, dedicated exclusively to hay production, had lower forage harvested. Alfalfa used for hay production may experience greater losses during various harvest operations, such as mowing, conditioning, raking, baling, pickup, and chamber compression. These losses are significantly influenced by moisture content and could potentially reach values close to 21% (Orloff & Mueller, 2008).

Timing of the final cut also varied, with Groups 1 and 2 finishing in August or early September, while Group 3 with later cuts in September, potentially increasing the risk of winter kill the following year. This aligns with the shorter cutting intervals in Groups 1 and 2, which focused on maximizing forage harvested and nutritional value, while Group 3 followed longer intervals, adhering more closely to the *Alfalfa management guide*'s stand persistence recommendations for the first three cuts (Undersander et al., 2011). However, in cases with more than three cuts, the final cut timing sometimes fell outside the recommended period. Groups 1 and 2 emphasized forage harvested and quality in the first two cuts while prioritizing nutritional value in the last two.

Stand persistence is a crucial factor in alfalfa production, and although this study did not directly assess stand longevity, it is important to consider that intensive management practices, such as frequent harvests, could potentially compromise long-term persistence if not carefully implemented. In the US Midwest, these intensive practices may lead to a gradual depletion of soil nutrients, which in turn can negatively impact plant growth, reduce overall productivity, and ultimately compromise the long-term persistence of alfalfa stands (Kallenbach et al., 2002).

The number of harvests in alfalfa should be considered carefully and depends on the objective of each stand. Alfalfa harvest can be adapted according to objectives such as maximizing persistence, achieving high nutritional value, or optimizing forage harvested and nutritional value simultaneously. If the goal is to harvest for the persistence of the stand, the plants should be cut between the first flower and 25% flower, which means around 35–40 days between cuttings and will probably allow three harvests (Undersander et al., 2011), as seen in Group 3. Cutting at full flower benefits alfalfa persistence as it maximizes nonstructural carbohydrate concentrations in the root and crown. The negative effects of frequent cutting can be mitigated if alfalfa flowers at least once annually before cutting to allow for adequate storage of nonstructural carbohydrate reserves (Sheaffer et al., 1988). However, for optimal nutritional value, the initial harvest should occur early in the season, according to the calendar date suitable for the region, and subsequent harvests should be timed at the mid-bud stage, typically at intervals of 28–33 days during the early season and longer intervals toward the end of the season, allowing for up to four harvests during the season (Undersander et al., 2011), as seen in Groups 1 and 2. On the other hand, to achieve improved forage yield and nutritional value, an early first harvest should be followed by short intervals to ensure the subsequent harvests maintain high forage nutritional value. As the season progresses, forage nutritional value tends to decline more gradually, enabling later cuttings to retain nutritional value for longer periods. This approach allows for three to four harvests within a growing season (Undersander et al., 2011). Other studies in the Mollisol agricultural area in China have similarly demonstrated that increasing the frequency of cutting, combined with fertilization, can significantly enhance both the forage harvested and the nutritional value of alfalfa (Gong et al., 2021).

Nevertheless, to reduce potential winter damage in the US Midwest and encourage vigorous spring growth in alfalfa, it is crucial to ensure that the plant stores enough root carbohydrates and proteins before going dormant (Jarek et al., 2021; Undersander et al., 2011). This requires harvesting the alfalfa early enough in the fall for the plant to replenish its energy reserves consumed during regrowth (Jarek et al., 2021). The critical fall period occurs 6 weeks before the first killing frost, especially when the time between previous cuttings has been 35 days or less. This timeframe typically falls between September 1 and October 15 in northern states, and later in southern states (Undersander et al., 2011). In the fields studied, most farmers (73%) finished their final cut in late August or early September, which aligns with the critical window for plant regrowth. Timing these final cuts well is essential for ensuring the plants store enough energy for the winter and regrow successfully the following year (Undersander et al., 2011).

Fall cutting of alfalfa, when timed appropriately, can be done without negatively affecting DM yield (McDonald et al., 2021). While fall cutting has traditionally posed challenges to alfalfa stand persistence, leading to cautious recommendations, recent advancements in disease resistance, the development of well-suited cultivars, and improvements in soil fertility have increased flexibility in fall-cutting practices. Despite these advancements, the impact of fall cutting remains highly dependent on environmental factors, such as air temperature and snowfall (Sheaffer et al., 1988).

Climatic conditions across the farms were relatively consistent and thus did not contribute significantly to the observed variability in cutting schedules. The differences in management practices were more likely driven by the different objectives and strategies of each farm, which is typical in on-farm research. Despite this variability, trends within each group remained consistent and aligned with the harvest management categories recommended by Undersander et al. (2011).

In this study, RFV exhibited variability among fields, averaging 140 among groups (ranging from 113 to 177), indicating overall good nutritional value of the stands. The RFV is determined by the ADF and NDF contents in the plant. ADF assesses the levels of cellulose and lignin in forage, closely correlating with digestibility and helping to estimate energy content. NDF evaluates total fiber content, including hemicellulose, and is linked to livestock DMI since it influences forage volume (Jeranyama & Garcia, 2004). According to Undersander et al. (2011), an RFV greater than 125 suggests that alfalfa is suitable for feeding dairy cows (*Bos taurus*) during late lactation, as well as heifers and stocker cattle.

Groups 1 and 2 demonstrated stable levels of CP and fiber content across cuts, ensuring consistent nutritive value in later harvests. Alfalfa nutritional value generally stabilizes in later cuttings compared to earlier ones, contributing to better nutritional value maintenance at advanced maturity stages (Brink & Marten, 1989; Undersander et al., 2011). Conversely, Group 3 began with the lowest CP and showed increases by Cut 4 but also revealed considerable variability. These results are likely connected to the cutting intervals observed among the groups. Groups 1 and 2 maintained relatively consistent intervals of 30 days (± 3) across all cuts. In contrast, Group 3 exhibited the longest and most variable intervals, averaging 46 days (± 13) between cuts, but 38 days (± 7) between the third and fourth cut. Group 3 had longer intervals between the initial cuts, which likely led to greater maturity of the alfalfa stands and an initial decline in nutritive value. In contrast, shorter intervals between the later cuts contributed to an improvement in the nutritional value of the final harvests, as evidenced by a reduction in fiber components and an increase in digestibility and RFV.

It is worth noting that while the technological groups identified in this study revealed different management strategies, the variation in practices within each group made direct comparisons more challenging. However, overall trends, such as Group 1 relying more on haylage and silage with greater use of inorganic fertilizers, Group 2 focusing more on haylage but relying more on organic sources like manure, and Group 3 emphasizing hay production with fewer cuts and lower input use, highlight clear distinctions in management intensity and objectives. Future studies could benefit from refining the grouping approach by reducing the range of management practices considered, which would improve the ability to compare among groups. This study highlights that there is not one single management practice that maximizes alfalfa forage harvested on farms, but rather a combination of practices is needed, depending on the objectives of the farmer. Group 1, which demonstrated a greater reliance on synthetic inputs and more intensive cutting strategies, achieved higher forage harvested, more closely aligning with productivity observed in research fields. In contrast, Group 2, which prioritized organic nutrient sources and reduced chemical inputs, harvested less forage, despite employing a similar cutting frequency to Group 1. Group 3, characterized by a more organic management approach, minimized input use and produced the lowest forage harvested, reflecting a focus on environmental sustainability at the expense of higher production.

Although this study did not assess the economic and environmental implications of these practices, it is crucial to consider the broader sustainability of alfalfa production. While the application of inputs and fertilizers can increase forage harvested, it is important to assess whether these increases offset the additional costs and environmental externalities. From an environmental perspective, excessive use of fertilizers can lead to leaching and groundwater contamination (Hussain et al., 2020). From a sustainability standpoint, it is crucial to find a balance between productivity, profitability, and environmental impact. The recommendation should not be merely to apply more nutrients but to design management strategies that optimize input use, minimize losses, and maximize system efficiency. This involves evaluating practices such as crop rotation, cover crops, and integration with other production systems (Davis et al., 2012; Kumari et al., 2024; Viguier et al., 2021).

Finally, the results of this study apply to the US Midwest, and it is important to recognize that agroclimatic conditions in other regions may yield different responses. Expanding this research to other geographic areas would help evaluate the broader applicability of these strategies in diverse agricultural contexts.

5 | CONCLUSIONS

This study identified key management practices associated with higher alfalfa forage harvested in the US Midwest, based on statistical analyses of 38 commercial fields monitored over two growing seasons. Fertilization with S, K, and B together with more frequent cutting, was consistently associated with increased forage harvested. These associations emerged from both univariate and multivariate analyses, including GLSs models and conditional inference trees.

Categorizing fields by forage use (hay, haylage, or silage), relative forage harvested and input use, revealed that silage and haylage systems tended to achieve greater values than hay systems. These higher yielding systems were also characterized by more intensive harvest schedules and larger nutrient applications. These patterns indicate that aligning forage use with harvest and fertility strategies may help reduce the gap between current and potential on-farm alfalfa forage harvested.

While these findings provide insights into management factors related to forage harvested under real farm conditions, further research is needed to assess how such practices affect long-term system sustainability. In particular, the impacts on economic returns, nutrient use efficiency, and soil health require additional investigation.

Overall, this study highlights the role of integrated management, including harvest intensity and nutrient inputs, in improving forage harvested in alfalfa farm systems in the US Midwest. Strengthening these strategies could contribute to both agronomic and environmental goals. However, as an observational study focused primarily on farms in Wisconsin, the findings may not fully represent conditions in other parts of the US Midwest or different agroecological regions. Causal inferences should be made with caution, and further research across diverse environments and over longer timeframes is needed to validate and expand on these insights.

AUTHOR CONTRIBUTIONS

Maria Soledad Orcasberro: Conceptualization; data curation; formal analysis; investigation; writing—original draft; writing—review and editing. **Nicole Tautges**: Conceptualization; methodology; project administration; resources; writing—original draft. **Daniel Undersander**: Conceptualization; investigation; writing—review and editing. **Marta Moura Kohmann**: Investigation; writing—review and editing. **Ines Berro**: Formal analysis; visualization. **Priscila Pinto**: Investigation; visualization; writing—review and editing. **Valentin Picasso**: Conceptualization; funding acquisition; investigation; project administration; supervision; writing—original draft.

ACKNOWLEDGMENTS

Funding from USDA AFRI NIFA SAS project #2021-68012-35917 (Fostering Resilience and Ecosystem Services in Landscapes by Integrating Diverse Perennial Circular Systems—RESILIENCE CAP), U.S. Alfalfa Farmer Research Initiative of the National Alfalfa & Forage Alliance (Closing the Alfalfa Yield Gap while Improving Soil Fertility and Health 2021 project) Midwest Forage Association (Closing Alfalfa Yield Gap 2020 project) was acknowledged for this work.

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SUPPORTING INFORMATION

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How to cite this article: Orcasberro, M. S., Tautges, N., Undersander, D., Kohmann, M. M., Berro, I., Pinto, P., & Picasso, V. (2025). Management practices that maximize alfalfa forage harvested on farms: Insights from technological groups. *Agronomy Journal*, *117*, e70177. https://doi.org/10.1002/agj2.70177