# Relationship between orchardgrass (Dactylis glomerata) dominance and the soil chemical characteristics of nonallophanic Andosol under cutting and cattle grazing

| | |
|---|---|
| 著者 | Hidetoshi Kakihara, Shin-ichiro Ogura |
| journal or publication title | Grassland Science |
| volume | 68 |
| number | 2 |
| page range | 165-173 |
| year | 2021-11-03 |
| URL | http://hdl.handle.net/10097/00136551 |

doi: 10.1111/grs.12354

# Relationship between orchardgrass (*Dactylis glomerata*) dominance and the soil chemical characteristics of non-allophanic Andosol under cutting and cattle grazing

Hidetoshi Kakihara and Shin-ichiro Ogura

Graduate school of Agriculture, Tohoku University, Ohsaki, Miyagi, Japan

Correspondence
Hidetoshi Kakihara, Graduate school of Agriculture, Tohoku University, Ohsaki, Miyagi, Japan 889-2192, Japan.
Email: kakihara@tohoku.ac.jp
Tel & fax: +81 (0)229-84-7382

## Abstract

Soil acidity affects botanical compositions and pasture production, but the relationship between orchardgrass persistence and the soil nutrients in acidic soils with different management methods is understudied in production fields. Here, using exchangeable acidity ($y_1$) as an indicator of exchangeable aluminum (Al), we conducted a survey to investigate the relationship between orchardgrass dominance and the soil characteristics in sown pastures under different management practices. The botanical composition and soil chemical conditions were investigated in six orchardgrass-tall fescue mixed pastures (two cutting meadows and four cattle grazing pastures) from June 18 to July 17, 2018. Six- and three-line transects were fixed in each meadow or pasture, respectively, and 5 measurement locations were set along each transect at 10 m intervals. Each location had three square plots (20 cm × 20 cm) for the vegetation survey and three consecutive soil sampling plots (4-cm diameter) adjacent to the middle square plot. The dominant plant species in each plot was recorded, and soil samples were collected at 0–5 cm depth to measure $y_1$ and major soil nutrients. The $y_1$ ranged from 3.55 to 25.83 in the cutting meadows, which was wider than in the grazing pastures (1.85–16.29). In the cutting meadows, the dominance frequency of orchardgrass increased with the rise in $y_1$, whereas that of tall fescue decreased in cutting meadows. No significant relationship was found between dominance frequencies and $y_1$ in the grazing pastures. Although concentration of some soil nutrients varied with $y_1$, these nutrients were not related to the dominance frequencies of orchardgrass for either management strategy. These results suggest that orchardgrass declines are prevented at high exchangeable Al sites by the non-establishment of less Al-tolerant plant species under cutting conditions.

KEYWORDS

Botanical composition, pasture management, pasture persistence, soil exchangeable aluminum, soil exchangeable acidity

## 1 | INTRODUCTION

Orchardgrass (*Dactylis glomerata*) is a widely used temperate forage grass because of its high productivity and nutritive value. However, the persistence of orchardgrass is reduced under excessive nitrogen application (Raese & Decker, 1966), low cutting height (Griffith & Teel, 1965), high air temperature (Drake, Colby, & Bredakis, 1963; Jones & Tracy, 2019), high soil moisture conditions (Jung & Baker, 1985), and soil acidity (Hojito, Higashida, Nishimune, & Takao, 1987; Poozesh, Castillon, Cruz, & Bertoni, 2010).

Soil acidity is a major factor affecting the botanical composition and pasture production (Curtin & Smillie, 1986; Hojito et al., 1987; Poozesh et al., 2010; Poozesh, Cruz, Choler, & Bertoni, 2007) because exchangeable aluminum (Al) in the soil dissolves into the soil solution as Al ions, which inhibits plant root elongation (Kochian, Hoekenga, & Piñeros, 2004). Acid tolerance differs among plant species, and some pasture species are more tolerant to Al than orchardgrass (Poozesh et al., 2007; Wheeler, Edmeades, Christie, & Gardner, 1992). Therefore, the low persistence of orchardgrass in acidic soils may be due to the direct effects of exchangeable Al or the indirect effects of other plant species (with higher soil acidity tolerance).

Soil acidification induces the accumulation of inorganic nitrogen (Aciego Pietri & Brookes, 2008; Kemmitt, Wright, & Jones, 2005) and causes deficiencies in the plant-available phosphorus and exchangeable cations in the soil (Follett & Wilkinson, 1985; Hojito et al., 1987; Naidu, Tillman, Syers, & Kirkman, 1990). The relative accumulation and deficiencies of these nutrients can also affect the persistence of sown pasture species. The soil and botanical characteristics of pastures differ under different pasture management practices, such as cutting and livestock grazing (Spedding & Diekmahns, 1972; Vallentine, 2001), suggesting that the management regimes have different impacts on the soil and pasture plants. However, in production fields, there is little available information on how much exchangeable Al varies within a pasture, and how it relates to orchardgrass persistence and soil nutrients, and how different pasture management affect these relationships.

Therefore, we conducted a field survey to obtain information on the variabilities of the soil exchangeable Al concentration within each pasture and its relationship to orchardgrass dominance and soil nutrients, and compared these relationships under cutting and cattle grazing managements, using six sown grasslands simultaneously renovated with orchardgrass and tall fescue.

## 2 | MATERIALS AND METHODS

### 2.1 | Study site

This study was conducted at the Kawatabi Field Science Center, Graduate School of Agricultural Science, Tohoku University (Ohsaki, Miyagi, Japan; 38.75°N, 140.76°E, 220–250 m above sea level). At this site, the annual rainfall is 1701 mm, and the mean air temperature is 10.5 °C (highest in August, 27.5 °C, and lowest in January –4.5 °C), based on records from 1990 to 2019 (Japan Meteorological Agency, 2020). The soil type is classified as a Haplic non-allophanic Andosol according to the Soil Classification System of Japan (The fifth committee for soil classification and nomenclature, 2017), a Pachic Melanudand according to Soil Taxonomy (Soil Survey Staff, 2014), or an Aluandic Andosol in The World Reference Base (WRB) classification (IUSS Working Group WRB, 2015).

Two cutting meadows (A, 1.0 ha; B, 2.0 ha) and four cattle grazing pastures (C–F with areas of 1.0–1.3 ha) were selected as survey sites (Table 1). Pastures C–F were part of the paddocks used for rotational beef cow grazing. All of the cutting meadows and grazing pastures were renovated in 2012 with orchardgrass (cv. Natsumidori) (20 kg of seeds ha$^{-1}$) and tall fescue (*Festuca arundinacea*, cv. Southern Cross) (15 kg of seeds ha$^{-1}$), which were broadcast seeded after herbicide application and seedbed preparation. The cutting meadows were harvested three times, in late May, early August, and early October. In 2018, the first cut was harvested June 4–17, and the herbage yields of meadows A and B were 4.1 and 5.2 t dry matter (DM) ha$^{-1}$, respectively. In the grazing pastures, beef cattle were rotationally grazed from late April to late October. In 2018, the average stocking rate was 3.3 cattle ha$^{-1}$, and total duration of grazing in pastures C to F were 83, 46, 52, and 95 days, respectively. As shown in Table 1, chemical fertilizer consisted of two inorganic compound fertilizer, urea, and fused magnesium phosphate was applied in late April, after the first and second cuts in the cutting meadows, and three to five times during the grazing period in the grazing pastures. Cattle manure compost was also applied to all of the cutting meadows and grazing pastures from November to December. The amounts of chemical fertilizer and cattle manure compost are shown in Table 1.

## 2.2 | Measurements

All measurements were conducted at fixed locations along line transects (50 m) established in the meadows and pastures (Figure 1). Parallel six- and three-line transects were fixed in each meadow and pasture, respectively, at a distance of 10 m. Five measurement locations for the vegetation survey and soil sampling were set along each transect at 10 m intervals (Figure 1). Each location had three plots (20 cm × 20 cm), and the center of each plot was set at a 50 cm interval.

Vegetation surveys and soil sampling were conducted from June 18 to July 17, 2018. The most dominant plant species was recorded as the species with the highest coverage in each plot. In this study, we assessed coverage because the persistence of forage grass, which is defined as a decline in the population of sown species in a community or the population that still express its trait (Parsons et al., 2010) and is distinguished from yield (Donald, 1963), were usually determined by tiller density or coverage (Jones & Tracy, 2018). Three consecutive soil cores (4 cm in diameter) were collected at 0–5 cm depth within an area away from the grass tussocks and dung pat and approximately 30 cm from the middle of the plot (Figure 1). The soil cores from each location were combined into a composite sample, dried at room temperature, sieved (2 mm) to remove gravel, and then stored for subsequent analysis. Soil pH was measured using 15 g of dried soil by dipping the glass electrode of a pH meter into a 1:2.5 soil to water suspension. The exchangeable acidity ($y_1$) was measured using 10 g of dried soil by titrating a 1 M potassium chloride (KCl) extract (soil:solution = 1:2.5) with 0.1 M sodium hydroxide (NaOH) to the endpoint of phenolphthalein (Mori & Shimada, 1970). The value of $y_1$ is closely related to the amount of KCl extractable Al (Saigusa, Shoji, & Takahashi, 1980), so $y_1$ was used as an indicator of exchangeable Al.

To analyze the soil nutrient contents, additional soil samples were collected after the third cut (November 20, 2018). One of the second measurement locations from the end of each line transect was alternatively chosen as the sampling location (Figure 1). The samples, each 80 cm$^2$ in area and 5 cm in depth, were collected using a hand shovel. Total nitrogen (Total-N), nitrate-nitrogen ($NO_3$-N), and ammonium-nitrogen ($NH_4$-N) were measured via the dry combustion, hydrazine sulfate reduction, and indo-phenol methods, respectively. Phosphorus pentoxide ($P_2O_5$) was determined via the Bray-2 method. Potassium oxide ($K_2O$), calcium oxide (CaO), and magnesium oxide (MgO) were evaluated by atomic absorption spectrometry after Schollenberger extraction.

### 2.3 | Data analysis

To compare the botanical compositions of cutting meadows and grazing pastures, the dominance proportion was calculated separately for orchardgrass, tall fescue and the other plant species. For example, the dominance proportion of orchardgrass was obtained by dividing the number of dominant plots of orchardgrass by the total number of plots in each cutting meadow (n = 90) and grazing pasture (n = 45). In this study, the dominance frequency of plants was also calculated in each location to analyze the relationships between the dominant plant species and the soil chemical characteristics. For example, the dominance frequency of orchardgrass in a location was evaluated by dividing the number of dominant plots of orchardgrass (0, 1, 2, or 3) by the total number of plots (n = 3), and were expressed as 0/3, 1/3, 2/3, or 3/3. The measurement locations were classified as “low” or “high”, depending on the median the concentration of soil nutrients (Total-N, $NO_3$-N, $NH_4$-N, $P_2O_5$ $K_2O$, CaO, and MgO).

The effects of $y_1$ and concentration of soil nutrients on the dominance frequency of plant species were assessed using multinomial logistic regression analysis (model 1) and a generalized linear mixed model (model 2), respectively. The effects of $y_1$ on the concentration of soil nutrients was evaluated using mixed linear regression analysis (model 3). The significance of these analyses was tested by likelihood ratio test (model 1), two-way analysis of deviance (ANODEV) (model 2), and ANOVA (model 3) with a significant level of 0.05.

In model 1, the logits of tall fescue and the other plant species versus orchardgrass (reference species) were fit as response variables, and the $y_1$ and each meadow/pasture were exploratory variables. Thus, each model is composed of two parts:

$$\ln(P_{TF}/P_{OG}) = \beta_{0\mathrm{TF}} + \beta_{1\mathrm{TF}} X + \beta_{2\mathrm{TF}} G,$$

$$\ln(P_{Others}/P_{OG}) = \beta_{0\mathrm{Others}} + \beta_{1\mathrm{Others}} X + \beta_{2\mathrm{Others}} G,$$

where $P_{TF}$ and $P_{Others}$ are the dominance frequencies of tall fescue and the other species, and $\ln(P_{TF}/P_{OG})$ and $\ln(P_{Others}/P_{OG})$ are logits of them versus the dominance frequency of orchardgrass ($P_{OG}$). The $X$ and $G$ are exploratory variables representing the $y_1$ and each meadows/pastures, respectively. The $\beta_{0\mathrm{FT}}$ and $\beta_{0\mathrm{Others}}$ are the intercept, $\beta_{1\mathrm{TF}}$ and $\beta_{1\mathrm{Others}}$ are the coefficients of variable $X$, and $\beta_{2TF}$ and $\beta_{2Others}$ are the coefficients of variable $G$.

In model 2, the dominance frequency of plant species was fit as the response variable with a binomial distribution, and the soil nutrient levels (lower or higher than the median value of the data set) and plant species were incorporated as fixed effects. The meadows/pastures were random effects. Thus, the model is given by:

$$\mathrm{logit}(q) = \beta_0 + \beta_1 N + \beta_2 S + \beta_3 I_{NS} + r \text{ (model 2)},$$

where $q$ is the dominance frequency of plant species, respectively. Variables $N$, $S$, and $I_{NS}$ represent the soil nutrient level, plant species, and the interaction between $N$ and $S$, respectively, $\beta_0$ is the intercept, $\beta_1$, $\beta_2$, and $\beta_3$ are the coefficients of the exploratory variables and their interaction, and $r$ is the random effect.

In model 3, the concentration of soil nutrients was fit as response variables. The $y_1$ was incorporated as a fixed-effect variable, and each meadows/pastures is a random-effect variable. Thus, the model is given by:

$$Y = \beta_0 + \beta_1 X + r,$$

where $Y$ are the concentrations of each soil nutrient, and $X$ is a variable representing the

$y_1$, $\beta_0$ and $\beta_1$ are the intercept and the coefficient of the exploratory variable *X*, respectively, and *r* is the random-effect variable.

All analyses were performed using the statistical software R version 3.6.1 (R Core Team, 2019). Multinomial regression analysis was conducted using the 'vglm', 'lrtest', and 'lrt.stat' function of the VGAM package (version 1.1.4). Generalized linear mixed modeling and ANODEV was performed using 'mixed' function of the afex package (version 0.27.2) and 'emmeans' function of the emmeans package (version 1.4.5). Mixed linear regression analysis was done using the 'lmer' function of the lime4 package (version 1.1.23) and 'anova' function of the base package.

## 3 | RESULTS

### 3.1 | Dominance proportion of plant species

The dominance proportion of orchardgrass ranged from 54–86% in the cutting meadows and 29–42% in the grazing pastures (Figure 2). The proportion of tall fescue, which was sown as an accompanying grass species when the pastures were established, was smaller in the cutting meadows (1–4%) than in the grazing pastures (9–33%). The other dominant plant species were redtop (*Agrostis alba*), broad-leaved dock (*Rumex obtusifolius*), sweet vernalgrass (*Anthoxanthum odoratum*), and mugwort (*Artemisia princeps*) in the cutting meadows, and water-pennywort (*Hydrocotyle ramiflora*), redtop, sweet vernalgrass, broad-leaved dock, and reed canarygrass (*Phalaris arundinacea*) in the grazing pastures.

### 3.2 | Soil acidity

Soil pH in the cutting meadows and grazing pastures ranged from 4.18. to 5.22 and 4.62 to 5.59, respectively.

The frequency distribution of $y_1$ differed between the cutting meadows and grazing pastures (Figure 3). The $y_1$ value ranged from 3.55. to 25.83 in the cutting meadows, which was greater than the values in the grazing pastures (1.85–16.29). The proportion of mildly acidic soil ($y_1$ = 0–5) was 8% in the cutting meadows and 35% in the grazing pasture. In contrast, the proportion of very strongly acidic soil ($y_1 > 15$) in the cutting meadows was 51.7% and only 1.6% in the grazing pastures.

### 3.3 | Effects of soil exchangeable acidity on the dominance frequency of plants and soil nutrient contents

The relationships between $y_1$ and dominance frequencies of orchardgrass, tall fescue, and the other plant species are shown in Figure 4. In the cutting meadows, the dominance frequency of orchardgrass increased with the rise in $y_1$, whereas the dominance frequency of tall fescue decreased (likelihood ratio test for the regression and the coefficient of $y_1$, $p < 0.05$). No relative variation was found between orchardgrass and the other plant species (likelihood ratio test for the coefficient of $y_1$, $p > 0.1$). In the grazing pastures, no significant regression was found between $y_1$ and dominance frequencies of the species (likelihood ratio test for the regression, $p > 0.1$).

The dominance frequencies of orchardgrass in the cutting meadows were higher in locations with lower soil $NO_3$-N and $NH_4$-N concentrations. In contrast, tall fescue was more dominant in grazing pasture locations with lower soil $NH_4$-N concentrations (pairwise multiple comparisons following ANODEV, $p < 0.05$; Figure 5).

The relationships between $y_1$ and concentration of soil nutrients are shown in Figure

6. The concentration of $NO_3$-N decreased with the decrease in $y_1$ in the grazing pastures (ANOVA, $p < 0.05$). With the increase in $y_1$, the concentration of CaO ($p = 0.05$) and MgO ($p = 0.07$) in cutting meadows tended to decrease and that of $NH_4$-N ($p = 0.09$) in the grazing pastures tended to increase (ANOVA, $p < 0.05$).

## 4 | DISCUSSION

In this study, most of the measurement locations in the cutting meadows and grazing pastures were classified as strongly acidic soil ($y_1 > 5$). Although the application of lime and compost at the time of pasture establishment would reduce the $y_1$ values (Matsuyama, Saigusa, & Kudo, 1999), most non-allophanic Andosols have $y_1$ values greater than 6 (Saigusa et al., 1980). Therefore, the study site represents a typical acid-soil grassland with non-allophanic Andosols.

We also observed variability in the soil acidity among measurement locations (Figure 3), which is consistent with previous studies (Morton, Baird, & Manning, 2000; Raun et al., 1998; Solie, Raun, & Stone, 1999). In contrast, temporal variations in the soil acidity are relatively small (Ball & Williams, 1968; Conyers, Uren, Helyar, Poile, & Cullis, 1997). These findings suggest that the spatial distribution of soil acidity is heterogeneous on a small scale and has different long-term effects on the plants growing in these areas.

The effect of $y_1$ on dominance frequencies of orchardgrass differed from that of tall fescue, that is, orchardgrass increased with the rise in $y_1$ while tall fescue decreased (Figure 4). Herbage yield decreases with soil acidification in orchardgrass pastures (Hojito, Sato, & Takao, 1983), but our results showed that orchardgrass dominated in strongly acidic locations more frequently than in mildly acidic locations. Tall fescue dominated in strongly acidic locations less than in mildly acidic locations (Figure 4). These results agree with prior work showing that orchardgrass dominance is better than tall fescue under acidic soil conditions (Clark, Zeto, Ritchey, & Baligar, 1997; Wheeler et al., 1992). Thus, the higher tolerance of orchardgrass to soil acidity may increase its relative dominance to tall fescue in the strongly acidic soils of cutting meadows. Although exact mechanism of the higher tolerance of orchardgrass relative to tall fescue has not yet been addressed, root length in unlimed acidic soil was longer in orchardgrass than tall fescue, whereas the length in limed soil were considerably longer in tall fescue than orchardgrass (Clark & Baligar, 2003), suggesting that root growth ability in acidic soil contributes to the difference in tolerance between these grasses.

The high dominance of orchardgrass in strongly acidic soils may also be due to the increased supply of soil nutrients from high soil concentrations of exchangeable Al. In general, soil acidity influences the accumulation and mineralization of nitrogen (Whitehead, 1995), the amount of available phosphorus (Naidu et al., 1990), and the exchangeable cations, such as potassium, calcium, and magnesium (Hojito et al., 1987). With increasing $y_1$, the concentration of $NO_3$-N in grazing pastures significantly decreased (Figure 6), and some soil nutrients, such as CaO and MgO in the cutting meadows tended to decrease and $NH_4$-N in the grazing pastures tended to increase. These relationships completely agree with previous study conducted under acidic soil condition (Follett & Wilkinson, 1985; Kemmitt et al., 2005). However, these soil nutrients were not related to the decrease in dominance frequencies of orchardgrass (Figure 5). Thus, the increase and decrease in these soil nutrient contents cannot explain well the variation of the dominance frequency of orchardgrass.

In this study, the relationship between $y_1$ and the dominance frequency of orchardgrass in grazing pastures differed from the patterns observed in cutting meadows (Figure 4). In the grazing pastures, $y_1$ was low, and its range was narrower than in the cutting meadows (Figure 3). Thus, the differences in $y_1$ distribution may influence the relationship between $y_1$ and the dominance frequency of orchardgrass. In general, soil acidification is accelerated by nitrogen fertilizers (Tian & Niu, 2015), and greater nitrogen deposition in the cutting meadows may have led to greater soil acidification, compared to the grazing pastures (Table 1). The deposition of cattle dung in the grazing pastures may delay soil acidification because the cattle dung can increase the soil pH (During & Weeda, 1973; During, Weeda, & Dorofaeff, 1973). Increased soil aggregation due to cattle grazing also decreases the soil acidification rate (Martins et al., 2014; Souza et al., 2010).

Moreover, the grazing activity of cattle (defoliation and trampling) strongly influences the botanical composition of grasslands (Vallentine, 2001), and cattle may disturb this relationship, as observed in the cutting meadows. For example, under grazing conditions, the defoliation rate is relatively high compared to cutting conditions. Water-soluble carbohydrates in the stubble play an important role in the growth of new leaves after defoliation and the persistence of orchardgrass, but high defoliation rates reduce the concentration of reserve carbohydrates (Davidson & Milthorpe, 1966). Cattle tend to prefer orchardgrass over tall fescue, which increases the selection and defoliation rates of this species (Baxter et al., 1986; Ridley, Lesperance, Jensen, & Bohman, 1963). In fact, the persistence of orchardgrass is poorer than that of tall fescue under continuous grazing conditions and high defoliation rates equivalent to rotational grazing (Brink, Casler, & Martin, 2010; Brummer & Moore, 2000).

Competition with other acid-tolerant plant species in the grazing pastures may have also affected orchardgrass dominance. Although the response to Al differs among cultivars and populations within plant species (Davies & Snaydon, 1973; Snaydon, 1970), the dominant species next to orchardgrass and tall fescue, such as red-top (Olsen & Chong, 1991), sweet vernal grass (Davies & Snaydon, 1973; Snaydon, 1970; Wu, Xin, & Sugawara, 2013), and broad-leaved dock (Miyagi, Uchimiya, Kawai-Yamada, & Uchimiya, 2013; Vondráčková et al., 2015), are highly tolerant to acidic soils and Al toxicity.

## 5 | CONCLUSIONS

In strongly acidic soils, orchardgrass may be more persistent than tall fescue and other plant species in sites with high exchangeable Al under cutting conditions. This trend is less clear under grazing conditions. To clarify the mechanism of the difference of these trends, further research needs to focus on the effect of grazing cattle on chemical properties of strongly acidic soil and growth of orchardgrass, and the competition among pasture plant species with different acid-tolerance.

The results of this study suggest that soil acidification can act advantageously for orchardgrass under cutting management. However, minimum amendments of soil acidity are necessary because strong soil acidification can cause deficiency of some elements such as phosphate and calcium in plants and a poor mineral balance in livestock.

## ACKNOWLEDGMENTS

This research was supported by the Project of Integrated Compost Science.

# REFERENCES

Aciego Pietri, J. C., & Brookes, P. C. (2008). Nitrogen mineralisation along a pH gradient of a silty loam UK soil. *Soil Biology and Biochemistry*, *40*(3), 797–802. https://doi.org/10.1016/j.soilbio.2007.10.014

Ball, D. F., & Williams, W. M. (1968). Variability of soil chemical properties in two uncultivated brown earths. *The Journal of Soil Science*, *19*, 379–391. https://doi.org/https://doi.org/10.1111/j.1365-2389.1968.tb01548.x

Baxter, H. D., Owen, J. R., Buckner, R. C., Hemken, R. W., Siegel, M. R., Bush, L. P., & Montgomery, M. J. (1986). Comparison of low alkaloid tall fescues and orchardgrass for lactating jersey cows. *Journal of Dairy Science*, *69*(5), 1329–1336. https://doi.org/10.3168/jds.S0022-0302(86)80539-2

Brink, G. E., Casler, M. D., & Martin, N. P. (2010). Meadow fescue, tall fescue, and orchardgrass response to defoliation management. *Agronomy Journal*, *102*(2), 667–674. https://doi.org/10.2134/agronj2009.0376

Brummer, E. C., & Moore, K. J. (2000). Persistence of perennial cool-season grass and legume cultivars under continuous grazing by beef cattle. *Agronomy Journal*, *92*(3), 466–471. https://doi.org/10.2134/agronj2000.923466x

Clark, R. B., & Baligar, V. C. (2003). Growth of forage legumes and grasses in acidic soil amended with flue gas desulfurization products. *Communications in Soil Science and Plant Analysis*, *34*(1–2), 157–180. https://doi.org/10.1081/CSS-120017423

Clark, R. B., Zeto, S. K., Ritchey, K. D., & Baligar, V. C. (1997). Growth of forages on acid soil amended with flue gas desulfurization by-products. *Fuel, 76*(8), 771–775. https://doi.org/10.1016/s0016-2361(97)00004-5

Conyers, M. K., Uren, N. C., Helyar, K. R., Poile, G. J., & Cullis, B. R. (1997). Temporal variation in soil acidity. *Australian Journal of Soil Research, 35*(5), 1115–1130. https://doi.org/https://doi.org/10.1071/S97022

Curtin, D., & Smillie, G. W. (1986). Effects of liming on soil chemical characteristics and grass growth in laboratory and long-term field-amended soils - II. Growth of Italian ryegrass (Lolium multiflorum) and bentgrass (Agrostis tenuis). *Plant and Soil*. https://doi.org/10.1007/BF02378849

Davidson, J. L., & Milthorpe, F. L. (1966). The effect of defoliation on the carbon balance in Dactylis glomerata. *Annals of Botany, 30*(118), 185–198. https://doi.org/10.1093/oxfordjournals.aob.a084066

Davies, M. S., & Snaydon, R. W. (1973). Physiological differences among populations of Anthoxanthum odoratum L. collected from the park grass experiment, Rothamsted II. Response to aluminium. *The Journal of Applied Ecology*, 47–55.

Donald, C. M. M. (1963). Competition among crop and pasture plants. *Advances in Agronomy*, *15*, 1–118.

Drake, M., Colby, W. G., & Bredakis, E. (1963). Yield of orchard grass as influenced by rates of nitrogen and harvest management. *Agronomy Journal*, *55*(4), 361. https://doi.org/10.2134/agronj1963.00021962005500040018x

Follett, R. F., & Wilkinson, S. R. (1985). Soil fertility and fertilization of forages. In M. E. Heath, R. F. Barnes, & D. S. Metcalfe (Eds.), *Forages: The science of grassland agriculture* (4th ed., pp. 304–317). Ames.

Griffith, W. K., & Teel, M. R. (1965). Effect of nitrogen and potassium fertilization, stubble height, and clipping frequency on yield and persistence of orchardgrass. *Agronomy Journal*, *57*(2), 147–149. https://doi.org/10.2134/agronj1965.00021962005700020006x

Hojito, M., Higashida, S., Nishimune, A., Takao, K., Hojito, M., Higashida, S., … Takao, K. (1987). Effects of liming on grass growth, soil solution composition, and microbial activities. *Soil Science and Plant Nutrition*, *33*(2), 177–185. https://doi.org/10.1080/00380768.1987.10557564

Hojito, M., Sato, T., & Takao, K. (1983). The acidifying of grassland accompanied with dissolved aluminum and its effects upon grass growth. *Bulletin of Hokkaido Prefectural Agricultural Experiment Stations*, *50*, 43-53 (in Japanese with English summary).

IUSS Working Group WRB. (2015). *World reference base for soil resources 2014, update 2015 International soil classification system for naming soils and creating legends for soil maps.*

Japan Meteorological Agency. (2020). Past weather data download. Retrieved July 13, 2020, from https://www.data.jma.go.jp/gmd/risk/obsdl/index.php

Jones, G. B., & Tracy, B. F. (2018). Persistence and productivity of orchardgrass and orchardgrass/alfalfa mixtures as affected by cutting height. *Grass and Forage Science*, *73*(2), 544–552. https://doi.org/10.1111/gfs.12309

Jones, G. B., & Tracy, B. F. (2019). Survey of orchardgrass persistence in the Mid-Atlantic states. *Crop, Forage & Turfgrass Management*, *5*(1), 180003. https://doi.org/10.2134/cftm2018.01.0003

Jung, G. A., & Baker, B. S. (1985). Orchardgrass. In M. E. Heath, R. F. Barnes, & D. S. Metcalfe (Eds.), *Forages: The science of grassland agriculture* (4th ed., pp. 224–

232). Ames.

Kemmitt, S. J., Wright, D., & Jones, D. L. (2005). Soil acidification used as a management strategy to reduce nitrate losses from agricultural land. *Soil Biology and Biochemistry*, *37*(5), 867–875. https://doi.org/10.1016/j.soilbio.2004.10.001

Kochian, L. V., Hoekenga, O. A., & Piñeros, M. A. (2004). How do crop plants tolerate acid soils? Mechanisms of aluminum tolerance and phosphorous efficiency. *Annual Review of Plant Biology*, *55*(1), 459–493. https://doi.org/10.1146/annurev.arplant.55.031903.141655

Martins, A. P., Costa, S. E. V. G. d. A., Anghinoni, I., Kunrath, T. R., Balerini, F., Cecagno, D., & Carvalho, P. C. de F. (2014). Soil acidification and basic cation use efficiency in an integrated no-till crop-livestock system under different grazing intensities. *Agriculture, Ecosystems and Environment*, *195*, 18–28. https://doi.org/10.1016/j.agee.2014.05.012

Matsuyama, N., Saigusa, M., & Kudo, K. (1999). Acidity of Japanese cultivated Andosols and Significance of exchange acidity y1 in their classification. *Japanese Journal of Soil Science and Plant Nutrition*, *70*(6), 754-761 (In Japanese with English summary).

Miyagi, A., Uchimiya, M., Kawai-Yamada, M., & Uchimiya, H. (2013). Impact of aluminium stress on oxalate and other metabolites in Rumex obtusifolius. *Weed Research*, *53*(1), 30–41. https://doi.org/10.1111/j.1365-3180.2012.00949.x

Mori, N., & Shimada, N. (1970). Acidity. In *The Methods of Soil Nutrient Analysis* (pp. 29–32). Tokyo: Yokendo (In Japanese only).

Morton, J. D., Baird, D. B., & Manning, M. J. (2000). A soil sampling protocol to minimise the spatial variability in soil test values in New Zealand hill country. *New*

*Zealand Journal of Agricultural Research*, *43*(3), 367–375. https://doi.org/10.1080/00288233.2000.9513437

Naidu, R., Tillman, R. W., Syers, J. K., & Kirkman, J. H. (1990). Lime-aluminium-phosphorus interactions and the growth of Leucaena leucocephala 1. Plant growth studies. *Plant and Soil*, *126*(1), 1–8. https://doi.org/https://doi.org/10.1007/BF00041363

Olsen, F. J., & Chong, S. K. (1991). Reclamation of acid coal refuse. *Landscape and Urban Planning*, *20*(4), 309–313. https://doi.org/10.1016/0169-2046(91)90004-6

Parsons, A. J., Edwards, G. R., Newton, P. C. D., Chapman, D. F., Caradus, J. R., Rasmussen, S., & Rowarth, J. S. (2010). Past lessons and future prospects: plant breeding for cool temperate pastures. In *Proceedings of the 4th Australasian Dairy Science Symposium* (pp. 272–291).

Poozesh, V., Castillon, P., Cruz, P., & Bertoni, G. (2010). Re-evaluation of the liming-fertilization interaction in grasslands on poor and acid soils. *Grass and Forage Science*, *65*(2), 260–272. https://doi.org/10.1111/j.1365-2494.2010.00744.x

Poozesh, V., Cruz, P., Choler, P., & Bertoni, G. (2007). Relationship between the Al resistance of grasses and their adaptation to an infertile habitat. *Annals of Botany*, *99*(5), 947–954. https://doi.org/10.1093/aob/mcm046

R Core Team. (2019). R: A language and environment for statistical computing. Retrieved June 21, 2019, from https://www.r-project.org/

Raese, J. T., & Decker, A. M. (1966). Yields, stand persistence, and carbohydrate reserves of perennial grasses as influenced by spring harvest stage, stubble height, and nitrogen fertilization. *Agronomy Journal*, *58*(3), 322–326. https://doi.org/10.2134/agronj1966.00021962005800030023x

Raun, W. R., Johnson, G. V., Stone, M. L., Whitney, R. W., Lees, H. L., Sembiring, H., & Phillips, S. B. (1998). Micro-variablity in soil test, plant nutrient, and yield parameters in bermudagrass. *Soil Science Society of America Journal*, *62*(3), 683–690. https://doi.org/10.2136/sssaj1998.03615995006200030020x

Ridley, J. R., Lesperance, A. L., Jensen, E. H., & Bohman, V. R. (1963). Relationship of animal preference to botanical composition of irrigated pastures. *Journal of Dairy Science*, *46*(2), 128–130. https://doi.org/10.3168/jds.S0022-0302(63)88986-9

Saigusa, M., Shoji, S., & Takahashi, T. (1980). Plant root growth in acid andosols from northeastern Japan 2 Exchange acidity y1 as a realistic measure of aluminum toxicity potential. *Soil Science*, *130*(5), 242–250.

Snaydon, R. W. (1970). Rapid population differentiation in a mosaic environment. I. The response of Anthoxanthum odoratum populations to soils. *Evolution*. https://doi.org/10.2307/2406802

Soil Survey Staff. (2014). *Keys to Soil Taxonomy* (12th ed.). Washington, DC: USDA-Natural Resources Conservation Service.

Solie, J. B., Raun, W. R., & Stone, M. L. (1999). Submeter spatial variability of selected soil and bermudagrass production variables. *Soil Science Society of America Journal*, *63*(6), 1724–1733. https://doi.org/10.2136/sssaj1999.6361724x

Souza, E. D. de, Costa, S. E. V. G. de A., Anghinoni, I., Carvalho, P. C. de F., Oliveira, E. V. F. de, Martins, A. P., … Andrighetti, M. (2010). Soil aggregation in a crop-livestock integration system under no-tillage. *Revista Brasileira de Ciência Do Solo*. https://doi.org/10.1590/s0100-06832010000400033

Spedding, C. R. W., & Diekmahns, E. C. D. (Eds.). (1972). Response to management and environment. In *Grasses and Legumes in British Agriculture* (pp. 133–148). Farnham Royal, Bucks: Commonwealth Agricultural Bureaux.

The fifth committee for soil classification and nomenclature. (2017). *Soil classification system of Japan*. The Japanese soiety of pedology. Retrieved from http://pedology.jp/soilclassification.html

Vallentine, J. F. (2001). Grazing effects on plants and soil. *Grazing Management*. https://doi.org/10.1016/b978-012710001-2/50245-8

Vondráčková, S., Száková, J., Drábek, O., Tejnecký, V., Hejcman, M., Müllerová, V., & Tlustoš, P. (2015). Aluminium uptake and translocation in al hyperaccumulator Rumex obtusifolius is affected by low-molecular-weight organic acids content and soil pH. *PLoS ONE, 10*(4), 1–18. https://doi.org/10.1371/journal.pone.0123351

Wheeler, D. M., Edmeades, D. C., Christie, R. A., & Gardner, R. (1992). Effect of aluminium on the growth of 34 plant species: A summary of results obtained in low ionic strength solution culture. *Plant and Soil*, *146*(1–2), 61–66. https://doi.org/10.1007/BF00011996

Whitehead, D. C. (1995). Amounts, sources and fractionation of organic nirtogen in soils. In *Grassland nitrogen* (pp. 82–107). Wallingford: CAB International.

Wu, E., Xin, G., & Sugawara, K. (2013). Effects of arbuscular mycorrhizal fungi on grass and weed in acidic andosol. *Applied Mechanics and Materials, 281*, 664–669. https://doi.org/10.4028/www.scientific.net/AMM.281.664

**TABLE 1** Annual management of the cutting meadows and cattle grazing pastures used in this study

| | Area (ha) | Chemical fertilizer | | | | | | | Cattle manure compost (t ha$^{-1}$) |
|---|---|---|---|---|---|---|---|---|---|
| | | Fertilizer material† (kg ha$^{-1}$) | | | | Composition (kg ha$^{-1}$) | | | |
| | | CF212 | CF211 | Urea | Fused P | N | $P_2O_5$ | $K_2O$ | |
| Cutting meadow | | | | | | | | | |
| A | 1.0 | 120 | 365 | 74 | 67 | 131 | 62 | 60 | 5.1 |
| B | 2.0 | 166 | 252 | 72 | 60 | 117 | 54 | 58 | 5.0 |
| Grazing pasture | | | | | | | | | |
| C | 1.3 | 80 | 140 | 41 | 34 | 63 | 29 | 30 | 0.9 |
| D | 1.1 | 80 | 140 | 41 | 34 | 63 | 29 | 30 | 0.9 |
| E | 1.0 | 80 | 140 | 41 | 34 | 63 | 29 | 30 | 0.9 |
| F | 1.0 | 80 | 140 | 41 | 34 | 63 | 29 | 30 | 0.9 |

† CF212, inorganic compound fertilizer with 20% N, 10% $P_2O_5$, and 20% $K_2O$; CF211, inorganic compound fertilizer with 20% N, 10% $P_2O_5$, and 10% $K_2O$; urea, urea containing 46% N; fused P, fused magnesium phosphate with 20% $P_2O_5$, 12% MgO, and 20% SiO.

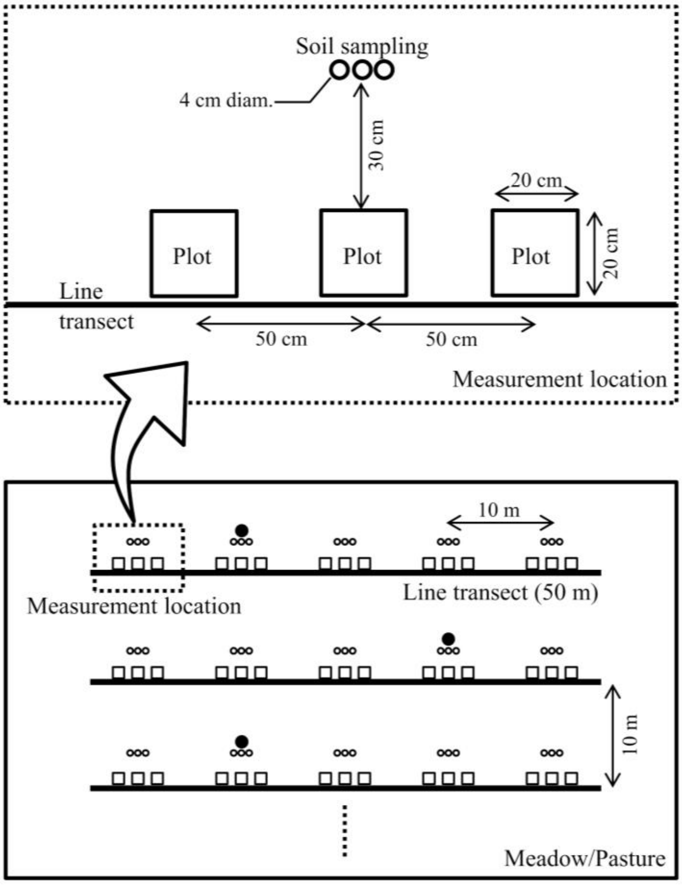

**FIGURE 1** Outline of the line transects and measurement locations. Five measurement locations, each consisting of three plots for vegetation surveys and one location for soil sampling, were set along each line transect at 10 m intervals. At each soil sampling location, three consecutive cores were collected from an area free of grass tussocks and dung. Filled circles represent additional sampling locations for soil nutrient analysis, which were included in one of the second measurement locations from the end of each line transect.

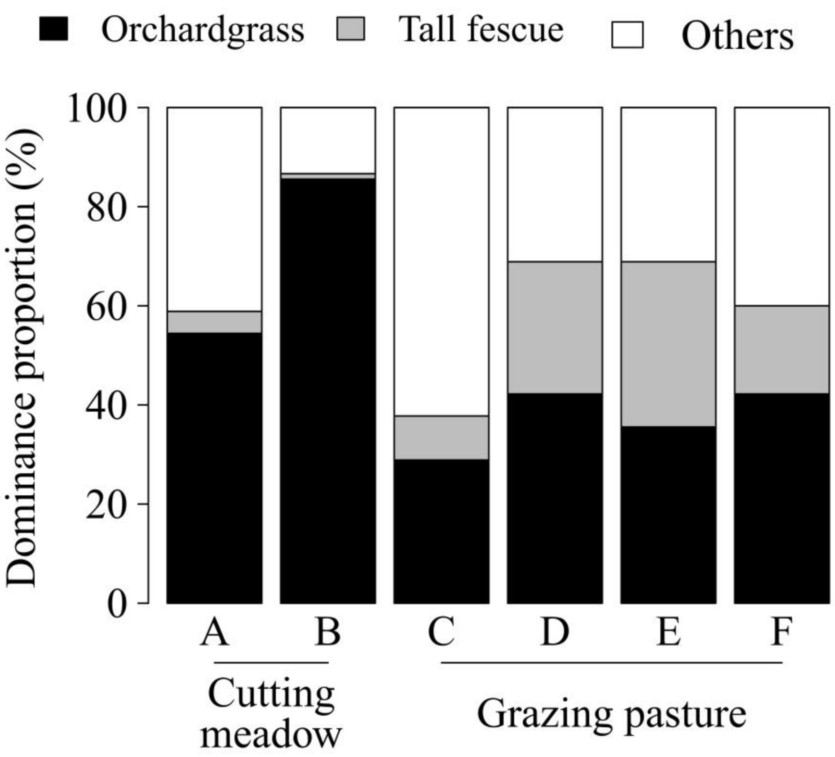

**FIGURE 2** Dominance proportion of each plant species in the study sites. A–F denotes the cutting meadows and grazing pastures.

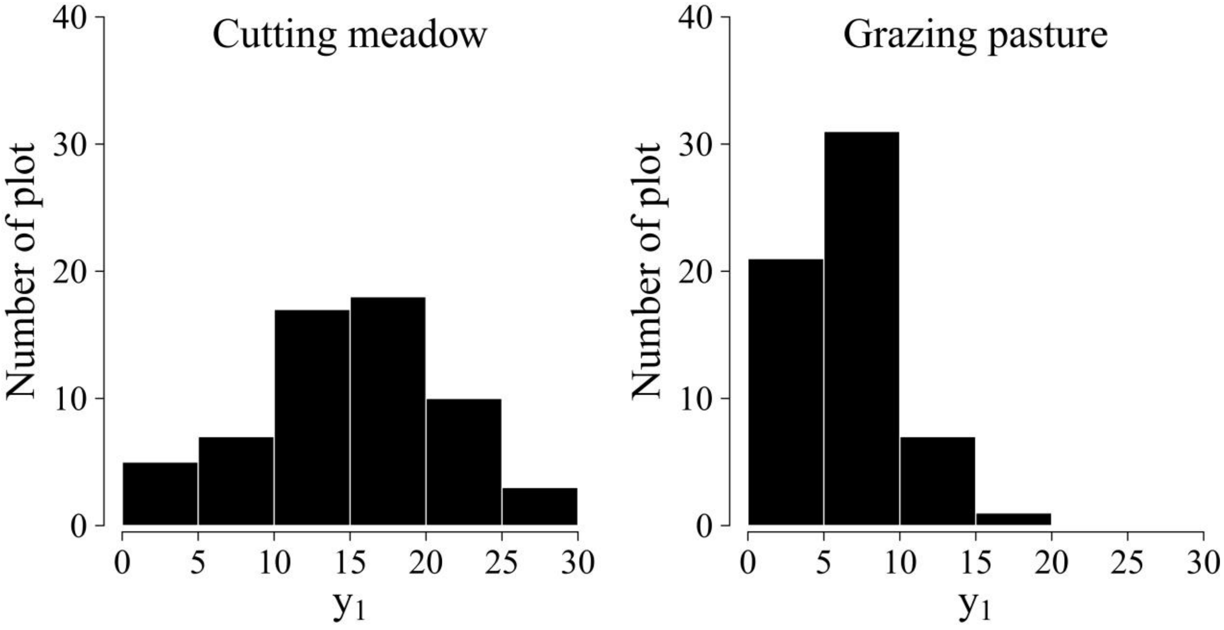

**FIGURE 3** Distribution of exchangeable acidity ($y_1$) in the cutting meadows (n = 60) and grazing pastures (n = 60).

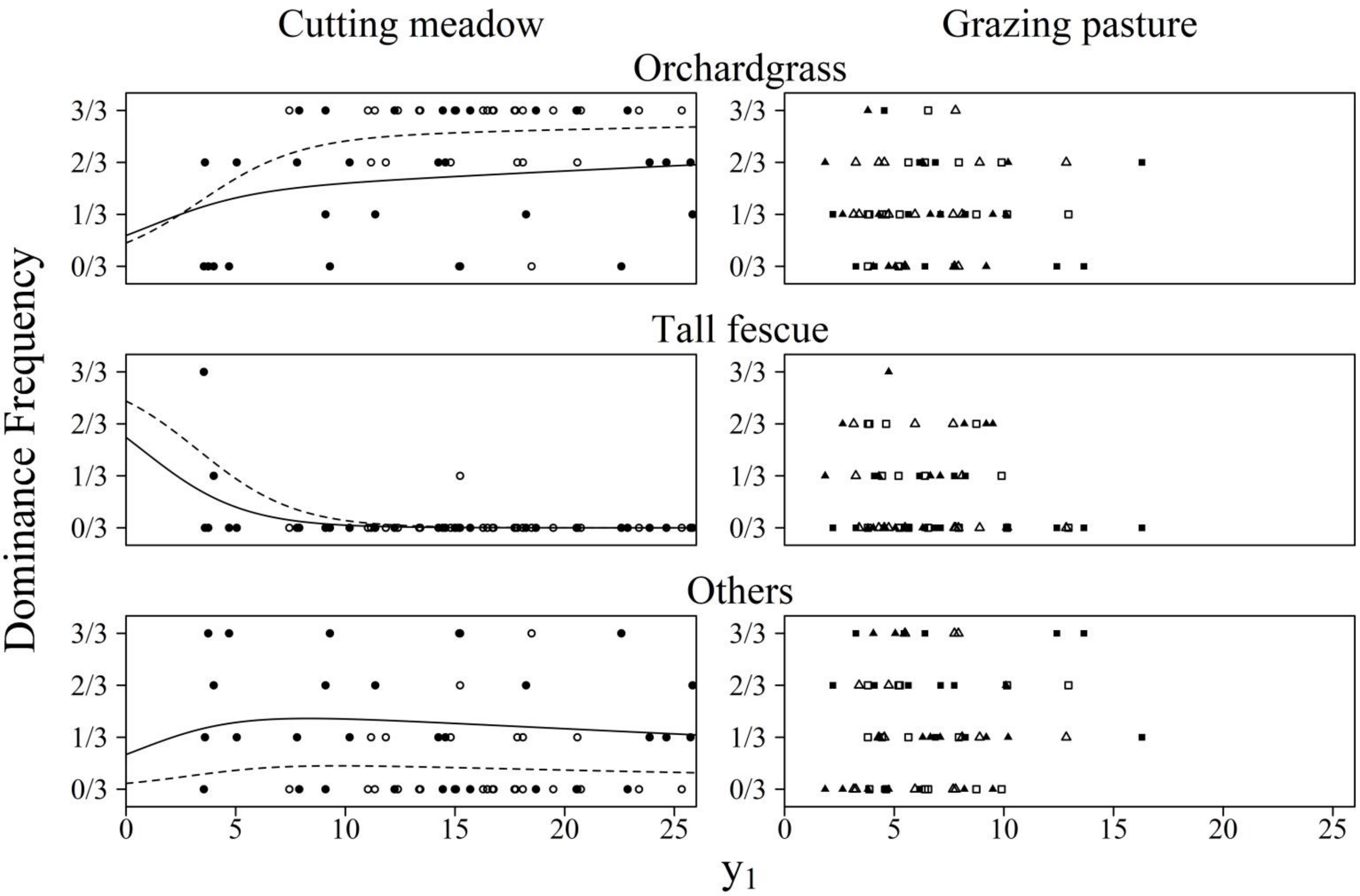

**FIGURE 4** Effects of soil exchangeable acidity ($y_1$) on dominance frequencies of orchardgrass (upper), tall fescue (middle), and the other plant species (lower) in the cutting meadows (left) and grazing pastures (right). Filled circles (●), open circles (○), filled square (■), open square (□), filled triangle (▲), and open triangle (△) denote soil samples in cutting meadow A and B and grazing pasture C to F, respectively. Solid curves (cutting meadow A) and dashed curves (cutting meadow B) represent multinomial logistic regression ($p < 0.05$).

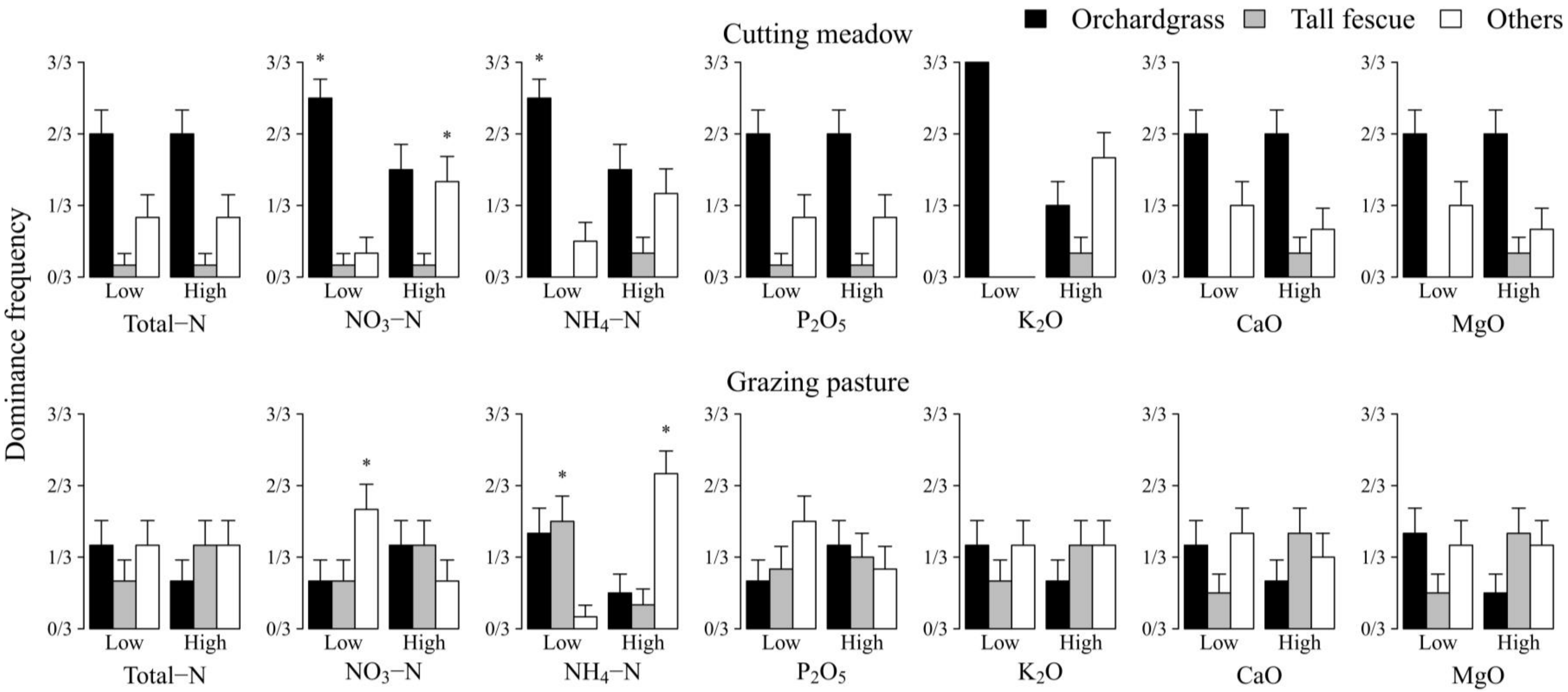

**FIGURE 5** Dominance frequencies of orchardgrass, tall fescue, and the other plant species at measurement locations with low and high soil nutrient contents (Total-N, $NO_3$-N, $NH_4$-N, $P_2O_5$, $K_2O$, CaO, and MgO) in the cutting meadows (upper) and grazing pastures (lower). For each soil nutrient, the measurement locations were classified as "low" (n = 6) or "high" (n = 6) based on the median value. Columns and bars represent the estimated marginal means and standard errors of the mean. Asterisks indicate significantly higher values than the other soil nutrients in each plant category ($p < 0.05$).

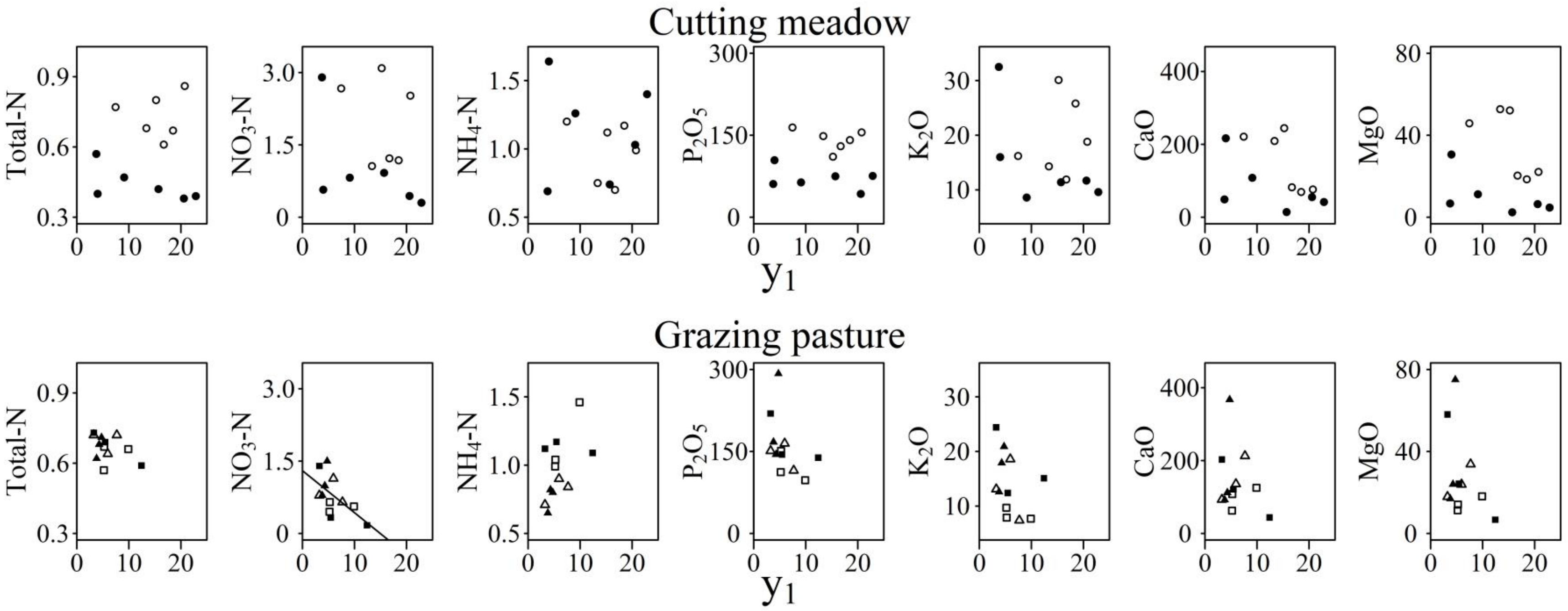

**FIGURE 6** Effects of soil exchangeable acidity ($y_1$) on the concentration of soil nutrients (Total-N, $NO_3$-N, $NH_4$-N, $P_2O_5$, $K_2O$, CaO, and MgO) in the cutting meadows (upper) and grazing pastures (lower). Filled circles (●), open circles (○), filled square (■), open square (□), filled triangle (▲), and open triangle (△) denote soil samples in cutting meadow A and B and grazing pasture C to F, respectively. A solid line represents a linear regression ($p < 0.05$, marginal pseudo-$R^2 = 0.33$). Units of concentration of soil nutrients are in (mg $100g^{-1}$) except for Total-N which is in (%).