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Abstract: Domestic livestock grazing is one of the dominant forms of land use globally. However, there are variable findings concerning the impacts of different grazing regimes on soil condition. We quantified the impacts of contrasting livestock grazing regimes on soil properties within nationally endangered temperate box-gum woodlands in south-eastern Australia. We sampled total soil nitrogen, phosphorus, carbon and bulk density at 65 woodland sites with a history of either continuous, strategic or rotational livestock grazing, as well as livestock grazing exclusion. We evaluated the influence of both historical and current management practices upon soil properties in the context of broad-scale soil forming factors such as climate, geology and topography.
We found evidence of a strong relationship between total soil phosphorus and nitrogen, while phosphorus also was influenced by site-scale native tree cover. Total soil phosphorus and nitrogen were related to the combined effects of pasture type and long-term fertilizer history (>10 years prior to sampling). No significant differences in soil nutrients or bulk density were detected between different grazing treatments, likely due to the importance of total grazing pressure (i.e. from all exotic and native herbivores) and the level of environmental variation between sites. However, total soil phosphorus was significantly higher in soils sampled in the season following a grazing event, irrespective of grazing intensity or duration. Total soil nitrogen and carbon exhibited a similar pattern. This is likely a result of multiple processes such as direct input of organic matter to the soil and stimulation of soil microbial communities. These findings have important implications for the strategic management of woodland understorey vegetation as soil nutrients have been identified as important drivers of native plant diversity.

Research Data Related to this Submission

Highlights

- Large-scale drivers of woodland soil and native vegetation management are explored
- Grazing appears to impact soil nutrients on a scale of weeks to months
- Environmental factors and fertiliser use affect nutrients in landscapes through time

Environmental and grazing management drivers of soil condition

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ABSTRACT

Domestic livestock grazing is one of the dominant forms of land use globally. However, there are variable findings concerning the impacts of different grazing regimes on soil condition. We quantified the impacts of contrasting livestock grazing regimes on soil properties within nationally endangered temperate box-gum woodlands in south-eastern Australia. We sampled total soil nitrogen, phosphorus, carbon and bulk density at 65 woodland sites with a history of either continuous, strategic or rotational livestock grazing, as well as livestock grazing exclusion. We evaluated the influence of both historical and current management practices upon soil properties in the context of broad-scale soil forming factors such as climate, geology and topography.

We found evidence of a strong relationship between total soil phosphorus and nitrogen, while phosphorus also was influenced by site-scale native tree cover. Total soil phosphorus and nitrogen were related to the combined effects of pasture type and long-term fertilizer history (>10 years prior to sampling). No significant differences in soil nutrients or bulk density were detected between different grazing treatments, likely due to the importance of total grazing pressure (i.e. from all exotic and native herbivores) and the level of environmental variation between sites. However, total soil phosphorus was significantly higher in soils sampled in the season following a grazing event, irrespective of grazing intensity or duration. Total soil nitrogen and carbon exhibited a similar pattern. This is likely a result of multiple processes such as direct input of organic matter to the soil and stimulation of soil microbial communities. These findings have important implications for the strategic management of woodland understorey vegetation as soil nutrients have been identified as important drivers of native plant diversity.

KEYWORDS: Soil nutrients; livestock grazing; agro-ecosystem; Australia

1. INTRODUCTION

Agro-ecosystems worldwide are under growing pressure due to global demand for increased food production and climate change (de Marsily and Abarca-del-Rio, 2015). Soil is a fundamental part of these ecosystems, and soil health is pivotal to maintaining both agricultural production and levels of biodiversity needed to maintain ecosystem resilience and provision of vital ecosystem services (Adhikari and Hartemink, 2016).

Domestic livestock grazing is the single most extensive form of land use on the planet and a significant component of the global food system (Asner et al., 2004; Williams and Price, 2011; IPBES, 2018). Up to 60 % of global lands that contribute to food production are considered either already degraded or used unsustainably (Montanarella and Vargas, 2012). However, it remains unclear how grazing might be best managed to promote soil health to both maintain agricultural production and conserve biodiversity (Dorrough et al., 2004; House et al., 2008; Tscharntke et al., 2012). Loss of native biodiversity has been linked to such problems as ongoing soil erosion, nutrient leaching, salinisation and reduction in water quality (Altieri, 1999; Eberbach, 2003; Tscharntke et al., 2012). Soil degradation directly impacts agricultural management through diminished productivity, increased management input costs, and reduced resilience to climatic change, including severe weather events (Adhikari and Hartemink, 2016).

Balancing environmental and agricultural objectives is a high priority for the management of endangered box-gum grassy woodland (BGGW) ecosystems in south-eastern Australia (Lindenmayer et al., 2012). These ecosystems occur on some of the most fertile agricultural land in Australia, but 95 % of their original cover has been cleared, leading to widespread biodiversity loss and soil degradation (Eberbach, 2003; Dorrough et al., 2004; Lindenmayer et al., 2016). Conserving and restoring BGGW is essential for maintaining ecosystem resilience and agricultural productivity in south-eastern Australia (Dorrough et al., 2004; Prober et al., 2014).

Prolonged grazing by domestic livestock is a known driver of ecosystem degradation in BGGW (Lunt et al., 2007). The majority of remnant BGGW patches have been utilized for livestock grazing (Spooner et al., 2002; Spooner and Briggs, 2008; Fischer et al., 2009; Lindenmayer et al., 2010). To promote recovery of degraded BGGW communities, it remains unclear whether woodland remnants are best fenced and left undisturbed, or whether controlled disturbance such as fire or episodic grazing is necessary to aid native plant regeneration and recover native biodiversity (Dorrough et al., 2004; Lunt et al., 2007; Prober et al., 2014). Episodic grazing may be used to control invasive exotic vegetation, promote regeneration of native species, and aid soil restoration (Dorrough et al., 2004; Fischer et al., 2009).

The most widely adopted form of livestock grazing in temperate Australia is continuous grazing (also referred to as ‘set stocking’), where grazing occurs at relatively low densities but livestock remain within a given area for extensive periods (Mavromihalis et al., 2013), often resulting in degradation of soil and vegetation communities (Teague et al., 2011). Prolonged continuous grazing can eventually lead to reduced livestock carrying capacity, increased soil compaction, re-distribution of nutrients, reduction in deep-rooted perennial grasses, and selective removal of more palatable vegetation species (Savory and Parsons 1980; Kemp et al. 2000; Dorrough et al., 2004; Mavromihalis et al., 2013).

Controlled grazing may assist restoration of degraded ecosystems by allowing land managers to influence vegetation communities (Kemp et al., 1996; Fischer et al., 2009; Lindenmayer et al., 2012) and cycling of organic matter at the soil surface (Teague et al., 2011; Waters et al., 2017; Orgill et al., 2018). High-intensity short-duration grazing (HISD grazing), also referred to as rotational grazing, cell grazing, holistic resource management or time control grazing (Earl and Jones, 1996; McCosker, 2000) are all forms of controlled grazing strategies. Along a gradient between continuous and HISD grazing, is the intermediate approach of strategic grazing (SG), where livestock are excluded during a set period of each year (in this case, spring and summer) to encourage desirable native species to set seed (Barnes and Hild 2013; Massey, 2017). During the remainder of the year, stock are moved between paddocks based on vegetative ground cover targets.

Understanding of the impacts of different grazing regimes on key aspects of soil condition is currently limited. To address this knowledge gap, we established a landscape-scale study of soil properties within replicated patches of BBGW. The spatial scale of our study is novel as it enables the overarching question to be tested: *Which environmental and grazing management factors influence major soil nutrients and soil bulk density?*

At the outset of this investigation, we made a series of predictions about soil responses. These were based on findings from earlier studies regarding organic litter decomposition (Post et al., 1982), fertilizer use and soil nutrients (Walker and Syers, 1976; Moir et al., 1997), pasture type and grazing strategies and soil nutrients (Prober et al., 2002a, Teague et al., 2011), and relationships between soil carbon and nitrogen and tree cover (Prober et al., 2002b). Specifically, we hypothesized that:

- Site-specific environmental drivers would primarily control rates of organic matter decomposition and therefore reflect total carbon (Post et al., 1982).
- Areas with high native tree cover would have high levels of soil organic matter due to greater leaf litter and manure inputs, and that this would be reflected in increased levels of total carbon and total nitrogen (Prober et al. 2002b).

- Fertilizer history followed by local geology would have a greater effect on total soil phosphorus (total phosphorus) than grazing strategy (Walker and Syers, 1976; Moir et al., 1997).
- Pasture type, in particular exotic-dominated pasture, would result in higher total nitrogen (Prober et al. 2002a).
- Grazing strategies which focus on pasture (HISD and strategically grazed) would result in higher levels of total Keldjahl nitrogen (total nitrogen) and total soil carbon (total carbon), along with lower bulk density (Teague et al., 2011).

2. <u>METHODS</u>

2.1 Study Region

We sampled 65 sites from 22 farms distributed over an area of 1.5 m ha in southern New South Wales, south-eastern Australia. These farms were part of a long-term agro-ecology study established in 2010 (TSSC, 2006; Lindenmayer et al., 2012; Barton et al., 2016; Sato et al., 2016) where the dominant land use is livestock grazing (by either sheep (*Ovis aries*) or cattle (*Bos taurus*)). Native vegetation cover consisted of patches of temperate box-gum woodland (BBGW) with an overstorey dominated or co-dominated by yellow box (*Eucalyptus melliodora* A.Cunn. ex Schauer), white box (*E. albens* Benth.), Blakely's red gum (*E. blakelyi* Maiden) or grey box (*E. microcarpa* Maiden) (DEH, 2006; TSSC, 2006).

2.2 Data Collection

We gathered remotely-sensed information using ArcGIS (version 10.4.1) on elevation, aspect, and percentage of woody vegetation cover within a 250 m radius of the central soil sampling point at each site (see Supplementary Table A.1 for full details). Digital mapping layers were sourced from the SEED portal of the New South Wales Office Planning and Environment (OPE, 2017). Site elevation was deemed to represent climatic variation between farms as per Badgery et al. (2014). We used local geological data sourced from digital maps (OPE, 2015), and then ground-truthed using field site assessments. We assigned slope position (upper, mid, lower) to each site in the field.

We assessed grazing management using four criteria; grazing management strategy, grazing intensity, time since grazing, and pasture management. We derived these data from landholder surveys. We assigned each site to one of five grazing management strategies: grazing exclusion (GE), continuous grazing (CG), long-conversion rotational grazing (LCR) (i.e. for c.a. 10 years prior to our study), short-conversion rotational grazing (SCR) (i.e. for c.a. 5 years prior to our study) and strategic grazing (SG) (no grazing through spring and summer, and vegetative groundcover of > 70 % to be maintained when grazed during the remainder of the year - c.a. 2 years prior to our study).

We defined grazing intensity as the total daily “Dry Sheep Equivalent” (DSE) (a standardised measure of feed requirements by different kinds of livestock) impacting each site during the period 2010-2011, averaged by the days in which grazing occurred (i.e. excluding days when the pasture was rested) (Kay et al., 2017).

Using information from landholder surveys, we categorized sites as either grazed or ungrazed in the three months prior to soil sampling.

The type of pasture and the fertilization of that pasture reflects farm management strategies and impacts soil properties. We assigned sites to one of three pasture management classes based on the frequency of fertiliser application and the type of pasture being grown at each site during the period 1991-2011 (as identified from landholder surveys). The three categories were: (i) Predominantly native pasture, not fertilized within the previous 20 years, but potentially receiving less than three fertilizer applications more than 20 years ago; (ii) Mixed native/exotic pasture, not fertilized within the previous 10 years, but potentially receiving less than three fertilizer applications more than 10 years ago; (iii) “Improved” pasture likely to contain purposely sown exotic species with fertiliser applied during the previous 10 years.

2.3 Soil sampling and laboratory analysis

We collected soils between August and December in 2011. At each site, sampling was undertaken at 12 points along a 200 m transect. We collected samples using mechanical coring to a depth of five centimeters, then air-dried and bulked in sets of four (with the samples numbered 1-4, 5-8, 9-12) to give a total of three composite samples per transect. We crushed samples to reduce aggregation and then removed particulate matter > 2 mm. We ground samples until particles were reduced to < 500 µm. We assessed total soil carbon (total carbon) through dry combustion using an Elementar Vario Max CNS analyser. We extracted total soil phosphorus (total phosphorus) and total Keldjahl nitrogen (total nitrogen) via Keldjahl digestion using concentrated H_2SO_4 at 350°C in the presence of K_2SO_4 and a copper catalyst. Following extraction, we determined nutrient content using flow-injection analysis and colorimetry.

We determined bulk density using soil bulk density cores (4.6 cm diameter 5 cm high) taken at 0-5 cm soil depth. Following careful removal of surface plant and litter biomass, we calculated the oven dry weight of soil per unit volume using the method described in Hazelton and Murphy (2007).

2.4 Statistical Analysis

To assess the influence of the selected environmental and management predictors on soil nutrients, we constructed individual hierarchical generalised linear mixed models (HGLM) (Lee et al., 2006) fit by maximum likelihood, using total phosphorus, total nitrogen, total carbon and bulk density as the response variables, and including farm and site as random effects to account for the nested study design. We assumed a normal distribution with an identity link for response variables, and for the random component. For each model, we included, as fixed effects, five environmental factors (elevation, aspect, native woody vegetation, geology and slope position) and four management factors (grazing strategy, grazing intensity, time since grazing and pasture management). We used Wald tests to assess the significance of each predictor variable included in the model and summarized the effects of interest using predictions adjusted for all other variables in the model (i.e. all other variables held at their means). We constructed all models using Genstat version 18.2.1.

3. RESULTS

We found that two environmental factors (geology and native woody cover in the surrounding landscape) and two management factors (time since grazing and pasture management) significantly altered total phosphorus and nitrogen, but not total carbon or bulk density soil properties. With regards to the effects of grazing regimes, grazing strategy and grazing intensity did not significantly influence soil properties. Rather, time since grazing was most important grazing regime covariate.

3.1 Influence of environmental factors on soils

We showed that total phosphorus and total nitrogen soil properties were significantly influenced by geology. Total phosphorus (χ^2_3 = 185.62, p < 0.001; Table 1, Figure 1a) and total nitrogen (χ^2_3 = 11.72, *p* = 0.008; Table 1, Figure 1b) levels were highest in soils formed from mafic volcanic geology and lowest in felsic and sedimentary soils.

Soils on sites surrounded by large amounts of native woody cover had significantly lower values of total nitrogen (χ^2_1 = 3.90, *p* = 0.048; Table 1, Figure 2). Other environmental variables including elevation, aspect and slope position did not significantly influence any modelled soil property (see Table 1, Supplementary Table A.2).

3.2 Influence of grazing management factors on soils

Time since grazing had a significant effect on total phosphorus (χ^2_1 = 8.70, *p* = 0.003; Table 1), with higher total phosphorus levels in recently grazed sites (i.e. grazed during the 3-month period prior to sampling or during sampling) compared with rested sites, irrespective of grazing type or duration (Figure 3). This pattern also was observed for total nitrogen (χ^2_1 = 3.60, *p* = 0.058; Supplementary Table A.2) and total carbon (χ^2_1 = 3.57, *p* = 0.059; Supplementary Table A.2) but was not significant for either soil property.

Predominantly native sites with fertiliser application prior to 1995 were characterized by significantly lower levels of total phosphorus (χ^2_1 = 16.33, *p* < 0.001; Table 1) and total nitrogen (χ^2_1 = 6.64, *p* = 0.036; Table 1), compared to either mixed native/exotic, or predominantly exotic, sites with fertiliser application between 1995 and 2005 (Figure 4a and b).

Other management variables including grazing strategy and grazing intensity did not significantly influence any modelled soil property (see Table 1, Supplementary Table A.2).

4. DISCUSSION

Soil is critical for both natural ecosystem function and agricultural productivity (Altieri, 2018; Heger et al., 2018). Livestock grazing has the capacity to alter a range of soil properties, yet the effects of different grazing regimes on BGGW soils have not previously been investigated. We quantified the influence of both historical and current management practices on the properties of soils from BGGW in the context of environmental influences such as geology, landscape position, and site-scale native woody vegetation. We then assessed the relative influence of livestock grazing in terms of grazing regimes (continuous, strategic or rotational grazing), grazing intensity (DSE averaged over days when livestock grazing occurred) and time since grazing.

4.1 Environmental and management factors with the greatest influence on soils

Felsic geologies studied here produce lower nutrient soils than mafic geologies (Figure 1) and this conforms to other published literature (Gray and Murphy, 1999). Globally, natural grassland ecosystems have evolved with lower nutrient soils and native herbivores (Milchunas and Lauenroth, 1993). However, as land use shifts towards managed grazing, higher fertiliser use is often used to sustain increased grazing pressure. The lower inherent nutrient status of felsic soils can lead to native pastures being less resilient to often higher intensity (sustained over longer durations per area) introduced grazing which can ultimately lead to changes in pasture abundance and composition (Bardgett et al., 1998). This may affect soil biological processes and a subsequent reduction of nutrient cycling (Brussaard et al. 2007). A reduction in these aspects of ecosystem function would result in less soil surface protection (e.g. from raindrop impact) and soil aggregation (Tisdall and Oades, 1982). Felsic soils in particular, given generally more coarse sediment textures, can be vulnerable to erosion (Wischmeier and Mannering, 1969; Koch et al., 2015). Application of fertilisers and sowing of exotic grass species are sometimes seen as a solution to rectify nutrient deficiencies, minimise soil loss, and ultimately maintain food for domestic livestock (Kemp and Dowling, 2000). Whilst not significant, this trend of higher levels of total nitrogen at those sites on felsic soils which had been more recently fertilised was observed and may be an outcome of complex interactions between management and underlying environmental drivers.

At the outset of this investigation, we postulated that sites surrounded by high levels of native tree cover would be characterized by relatively higher levels of soil organic matter due to localised patterns in the distribution of litter and manure, and that this would be reflected in increased levels of total carbon and total nitrogen (Manning et al., 2006; Prober et al., 2014). Unexpectedly, we observed trends showing negative relationships between all major nutrients and tree cover. This may be because timbered sites are commonly associated with less fertile soils, as naturally fertile areas have over time been preferentially cleared for agriculture (Fischer et al., 2010). Previous applications of fertiliser within cleared areas may have resulted in comparatively higher levels of soil nutrients in pastured areas (Prober et al., 2002a). Compounding this, fertiliser use encourages the growth of exotic annual species which commonly lead to further increase in soil nitrogen (Prober et al. 2002b; Dorrough et al. 2006). Consistent with these findings, our results showed fertiliser history and pasture type are important drivers of current patterns of soil nutrients. Sites fertilised in the previous 10 years also contained high proportions of exotic pasture species, and these sites supported significantly elevated levels of total phosphorus and nitrogen. Total carbon content did not follow this pattern, although sites with higher total phosphorus are commonly associated with correspondingly greater levels of soil carbon (Chan et al., 2010; Orgill et al., 2014).

We predicted that bulk density would decline close to trees, indicating improved soil structure due to a higher content of organic material (Wilson et al., 2002). The fact that bulk density was not significantly affected by tree cover at our sites (and, showed a weak positive relationship with tree cover) may be associated with livestock resting (‘camping’) beneath trees. We observed that soil disturbance caused by livestock camps reduced ground cover and appeared to produce harder soil surfaces, which most likely aided removal of organic surface soil via water erosion processes. This livestock behaviour and subsequent negative impact on both soil and vegetation community has been widely observed (Landsberg and Wylie, 1988; Yates et al., 2000; Schnyder et al., 2010). Mature trees in these landscapes have been identified as keystone structures and protecting them from such processes should be considered a priority for land management (Manning et al., 2006). Implementing HISD grazing is one strategy towards achieving this aim as livestock are restricted from camping in the same places for long periods.

Different soil properties are affected by different processes and this was reflected in our key findings. Total phosphorus is derived mainly through the process of mineral weathering or fertiliser application (Dorrough et al., 2006; Rui et al., 2012), both of which were likely to have had an important influence in our study. Sites associated with relatively nutrient-rich mafic geology had significantly higher levels of total phosphorus, as did sites fertilised during the previous 10 years.

Total nitrogen levels were lower at sites associated with nutrient-poor felsic geology. Soils derived from felsic rock are commonly coarse in texture, low in clay content and the clays that do form have low cation exchange capacity and fertility (Gray and Murphy, 1999). These soils require well-functioning biological processes to drive nutrient cycling as labile forms of nutrients such as nitrogen easily leach from the upper soil (Decau et al., 2003).

4.2 The effects of grazing on soil properties

A key finding of this study was the increase in total phosphorus in those soils which had been grazed either during sampling or within the 3-month period prior to sample collection (‘recent grazing’). A similar pattern was found for total nitrogen and total carbon. These results may be attributed to a series of concurrent processes: (i) direct input of organic matter and nutrients resulting from addition of manure/urine and trampling of above-ground biomass (Clegg, 2006; Semmartin et al., 2008), (ii) additional input of below-ground organic matter through the process of grass root die-off in response to grazing (Guitian and Bardgett, 2000), (iii) stimulation of soil microbial communities following input of organic matter and root exudates (Bardgett et al., 1998, Paterson and Sim, 1999), (iv) reduced plant uptake of nutrients following defoliation (Paterson and Sim, 1999), (v) redistribution of nutrients between rhizosphere, plant biomass and animal biomass (Rotz et al., 2005), and (vi) transport of nutrients via manure, urine or soil between paddocks either directly from stock (Oenema et al., 2007) or erosion processes (Fierer and Gabet, 2002; Chappell and Baldock, 2016).

It is likely that a period > 2 years may be required for grazing to precipitate major changes to equilibrium levels of total soil nutrients (Halvorson et al., 1997). The increases we observed in total phosphorus and carbon at recently grazed sites in this study capture a specific phase within the broader temporal nutrient cycle and most likely reflect a process of transitory nutrient fluctuation rather than a long-term increase in baseline nutrient levels. Orgill et al. (2018) concluded that while seasonal processes impact the more labile forms of carbon, detection of total carbon stocks under differing grazing systems occur over longer time frames (> 5 years). The cumulative effect of multiple biologically driven processes enhances soil community complexity, building ecosystem function and leading to increases in soil nutrients (Brussaard et al., 2007). Increased knowledge of short-term interactions between nutrient cycles and grazing will allow development of more effective restoration strategies for native woodland vegetation (Prober et al., 2014).

The different grazing regimes in our investigation (CG, LCR, SCR and SG) and grazing intensities had no significant influence on soil properties when compared with control sites where livestock had been excluded for 1-2 years. This contrasts with observations from other studies describing changes following livestock grazing exclusion in grassy woodlands. For example, Spooner et al. (2002) reported a small but significant reduction in soil compaction 2-4 years after livestock grazing exclusion, potentially reflecting natural soil rejuvenation processes. Due to environmental influences discussed in Section 4.1, determining soil response to long-term grazing management practices can be difficult at a landscape scale (Orgill et al., 2018), particularly across a broad range of land types such as those included in this study. For this reason, effects of a small magnitude (such as those resulting from a relatively recent (1-3 year) change in management (Halvorson et al., 1997)) may be difficult to detect. Yates et al. (2000) reported significant differences in both soil chemical and physical properties in grazed versus ungrazed woodlands, however the treatments in question had been in place for several decades.

The lack of significant difference between grazed and ungrazed sites from our study may also reflect the impacts of total grazing pressure rather than only livestock grazing activity. We noted during sampling that many of the ‘ungrazed’ control sites were acting as refuges for large numbers of native herbivores, a situation indicating that grazing pressure remained high despite the exclusion of domestic livestock. Previous research has shown that native herbivore grazing can significantly alter vegetation attributes (Howland et al., 2016), indicating that soil processes also may be affected.

The large spatial scale and access to property management records are key strengths of this study. However, associated with this comes heterogeneity of results driven by the environmental and management predictors themselves. Increasing replication across the diversity of predictors (e.g. number of sites on felsic soils = 142 versus 12 on mafic soils) would be preferable. However, considerable sampling logistics exist. The time required for sampling prohibits studying more transient forms of soil nutrients (e.g. nitrogen). The significance of total phosphorus in the study does suggest exploring plant available phosphorus would be a valuable addition. Maintaining landholder engagement in the future would allow for repeated sampling at decadal intervals, potentially increasing understanding of management impacts.

5. CONCLUSIONS

Our results provide new information on the management of woodland soils and native vegetation, emphasising the need to consider the timing of grazing events in the context of restoration planning, as well as the importance of long-term research when considering management impacts. We also highlighted the importance of both long- and short-term management history, as well as environmental variables, as factors influencing levels of soil nutrient. Our study suggests that grazing management has the potential to influence soil nutrients on a scale of weeks to months, but that this may reflect short-term fluctuations in nutrient levels rather than long-term trends. Our findings also emphasise the importance of broad-scale environmental variation and previous fertiliser use as factors affecting nutrient distribution at a landscape-scale. Grazing appears to be having a relatively immediate impact on soil nutrients. This type of knowledge has potential to inform restoration strategies applied to temperate grassy woodlands in south-eastern Australia.

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FIGURE CAPTIONS

Figure 1. Influence of geology on (a) total phosphorus and (b) total nitrogen. Error bars represent standard errors of the mean.

Figure 2. Influence of native woody cover in the surrounding landscape on total nitrogen. Error bars represent standard errors of the mean.

Figure 3. Influence of time since grazing on total phosphorus. Error bars represent standard errors of the mean.

Figure 4. Influence of pasture management on (a) total phosphorus and (b) total nitrogen. Error bars represent standard errors of the mean.

TABLE

Table 1. Significance of model terms testing the effects of environmental and land management on soil properties. Properties modelled include total soil phosphorus (total P), total Keldjahl nitrogen (total N), total soil carbon (total C), total bulk density (Bulk Density). Environmental variables include elevation, aspect, Native woody vegetation (Woody Vegetation), geology and slope position (Slope). Land management variables include grazing strategy, grazing intensity, time since grazing (Grazing Time) and pasture management (Fertiliser Application).

		total P	total N	total C	Bulk Density
	df	*Wald*	*Wald*	*Wald*	*Wald*
Environmental Variables					
Elevation	1	ns	ns	ns	ns
Aspect	1	ns	ns	ns	ns
Woody Vegetation	1	ns	3.90*	ns	ns
Slope	2	ns	ns	ns	ns
Geology	3	185.62***	11.72**	ns	ns
Management Variables					
Grazing Strategy	4	ns	ns	ns	ns
Grazing Intensity	1	ns	ns	ns	ns
Grazing Time	1	8.70**	ns	ns	ns
Fertiliser Application	2	16.33***	6.64*	ns	ns

*$P<0.05$, **$P<0.01$, ***$P<0.001$, ns = not significant.

Figure 1

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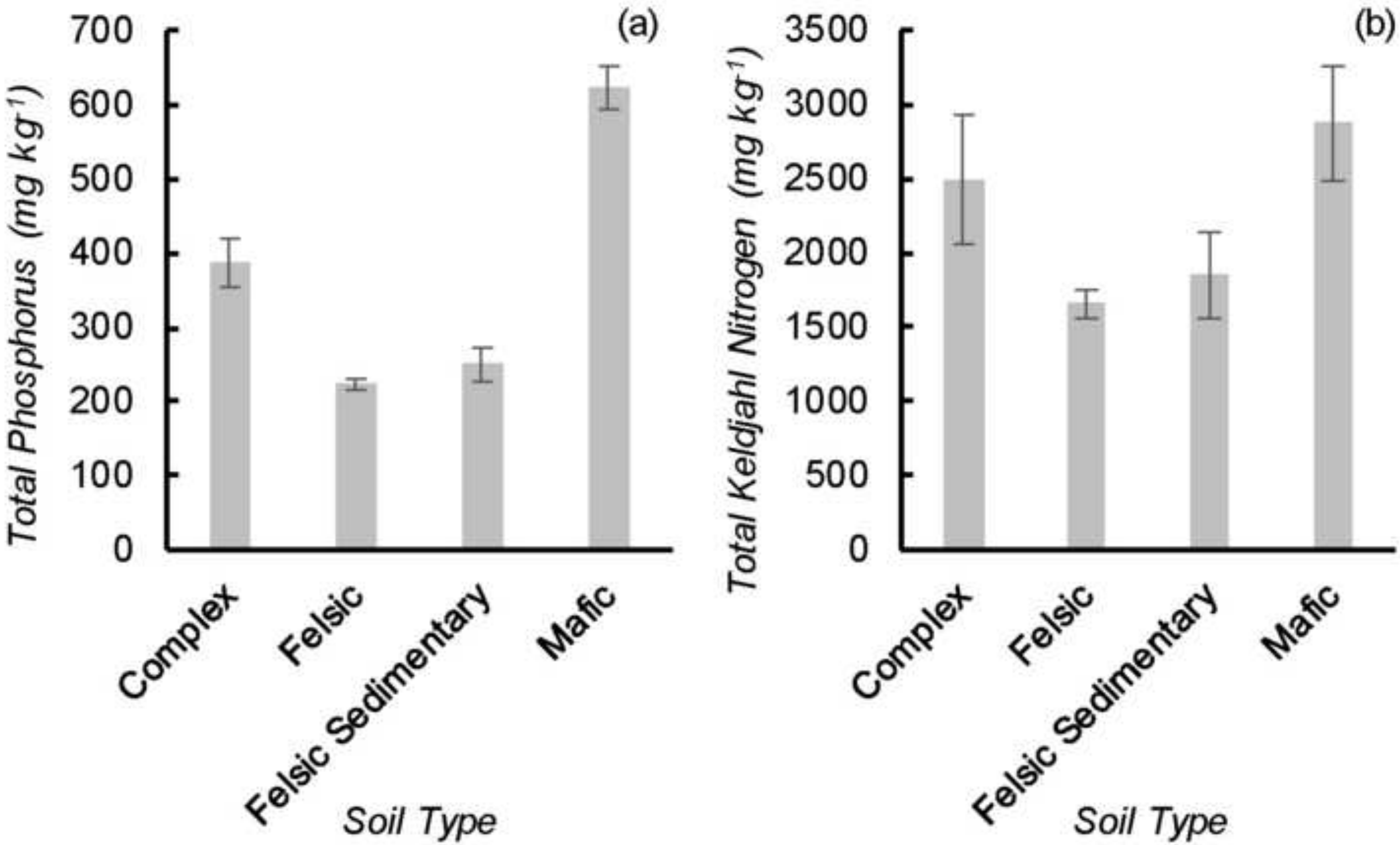

Figure 2

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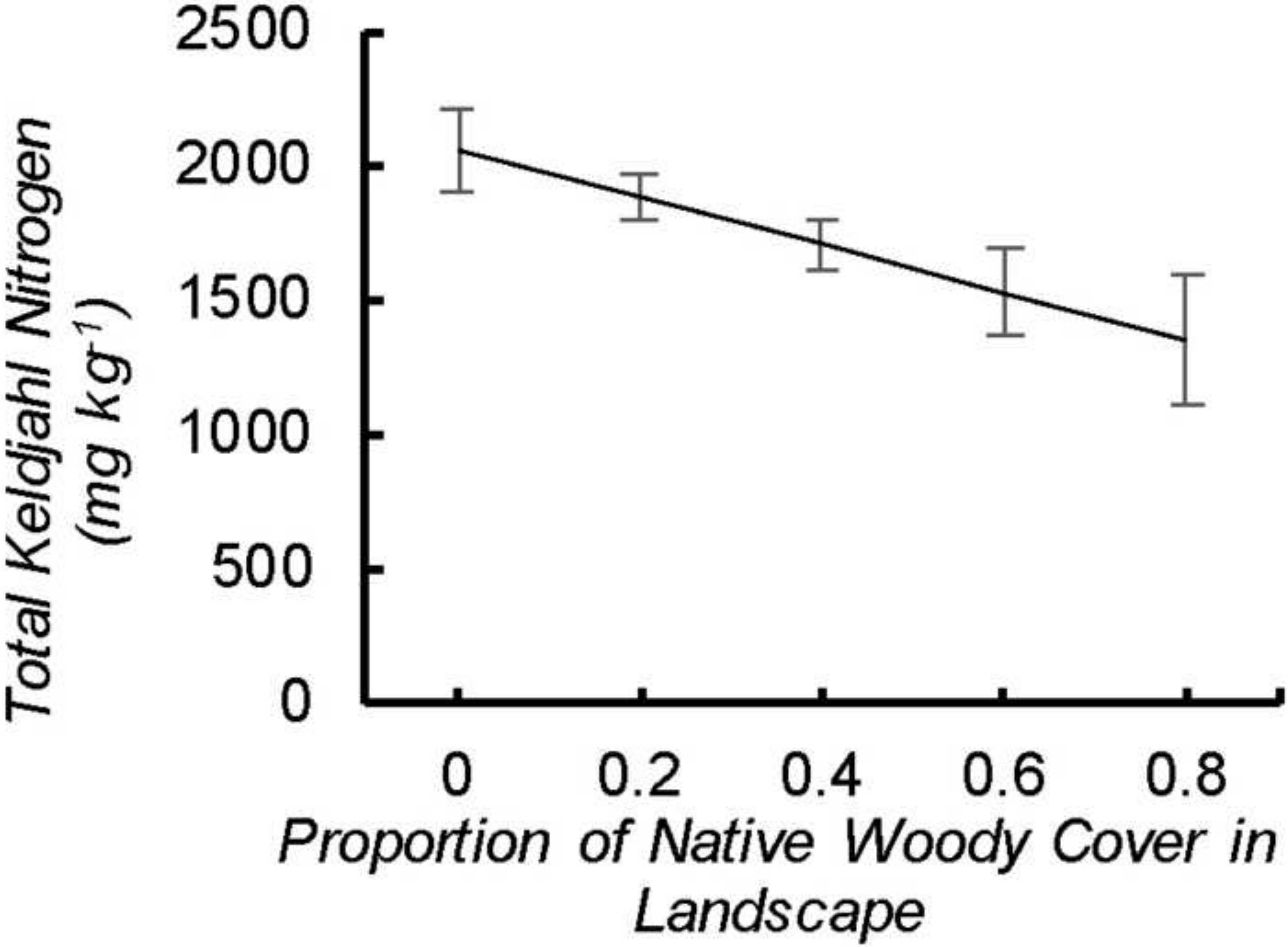


Figure 3

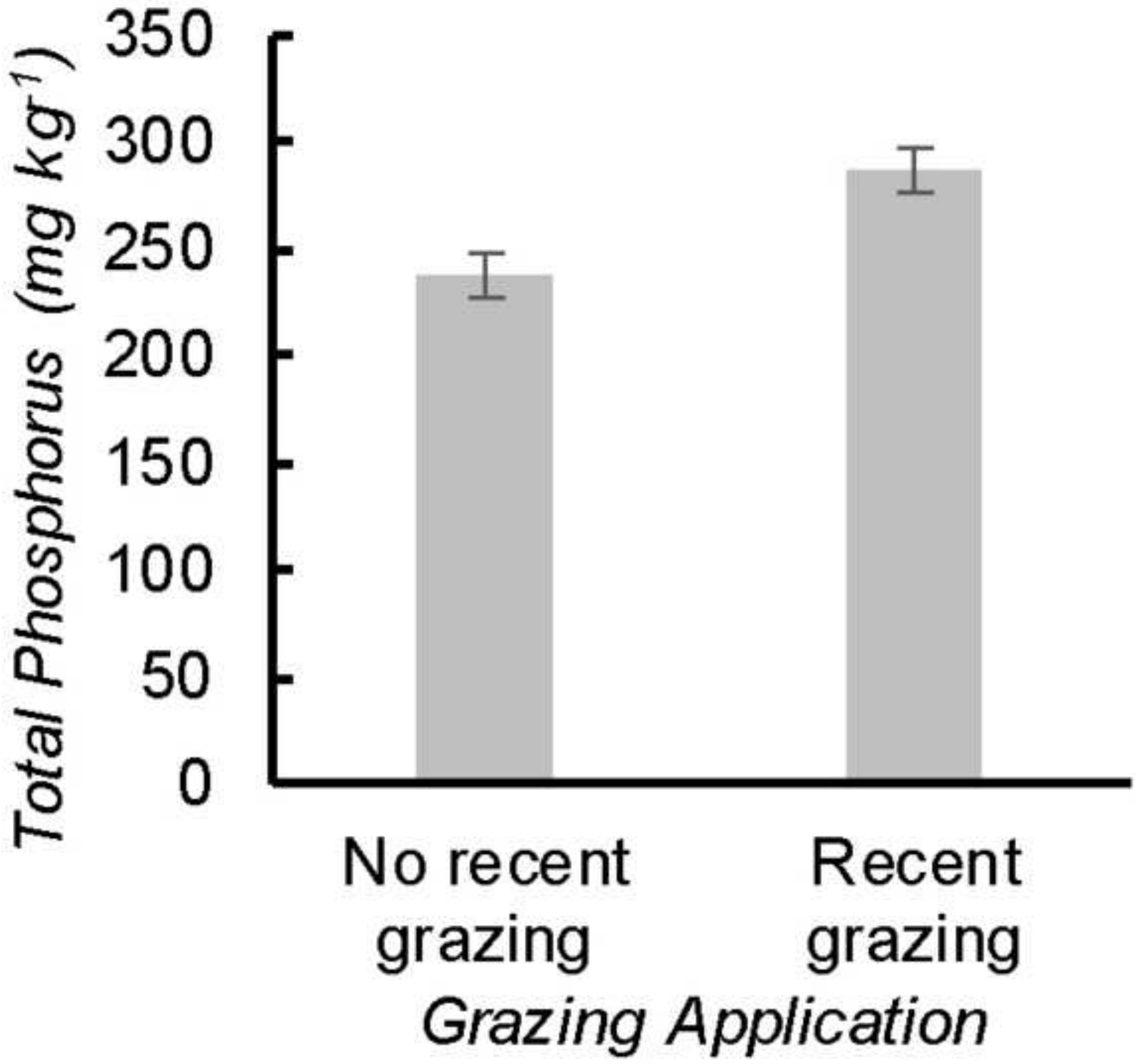
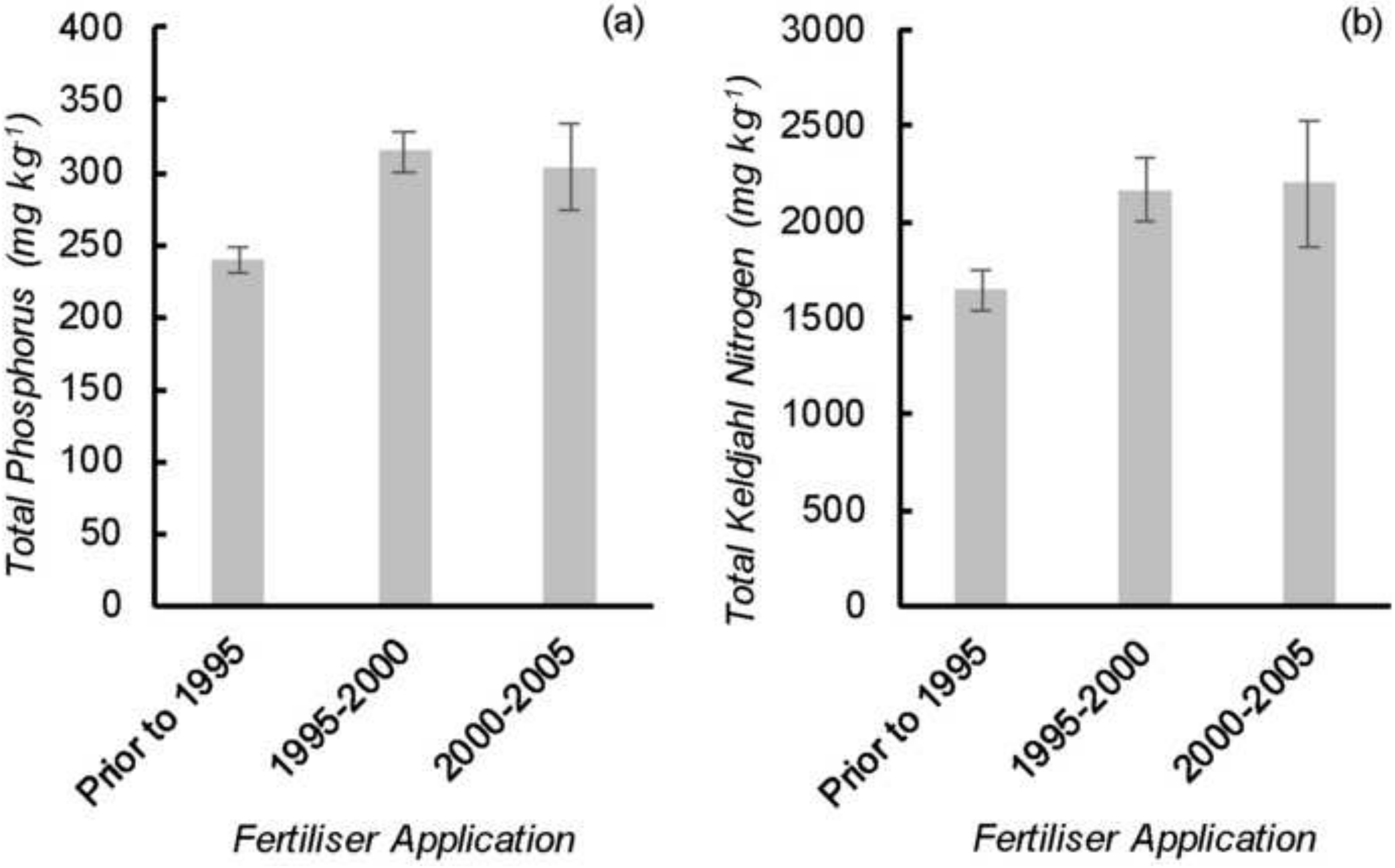

Total Phosphorus (mg kg^{-1})
350
300
250
200
150
100
50
0
No recent grazing
Recent grazing
Grazing Application

Figure 4


(a)
Total Phosphorus (mg kg-1)
400
350
300
250
200
150
100
50
0
Prior to 1995
1995-2000
2000-2005
Fertiliser Application
(b)
Total Keldjahl Nitrogen (mg kg-1)
3000
2500
2000
1500
1000
500
0
Prior to 1995
1995-2000
2000-2005
Fertiliser Application

Supplementary Material for publication online only