Evidence of nutrient, not soil pH, stratification in pasture soils in the Australian Capital Territory

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Abstract
There has been an increasing interest in the stratification of soil nutrients and pH, and the need to revise sampling depths to better diagnose soil surface and subsurface constraints to crop and pasture production. Twenty-three commercial paddocks were sampled in the Australian Capital Territory (ACT) to diagnose soil chemical constraints to 30 cm. There was little evidence of pH stratification, but strong evidence of phosphorus (P), sulfur (S) and potassium (K) accumulation in the surface (0-5 cm) soil. Nutrient concentrations were highest at 0-5 cm and declined significantly with depth, consistent with the trend in soil organic matter (indicated by total carbon and nitrogen concentration). Sixty six percent of paddocks had available P (0-10 cm) in excess of the critical value, while 61% were deficient in S (0-10 cm). There was no evidence of S accumulation in subsurface soil layers to 30 cm and overall 61% of paddocks were deficient in S in the 0-30 cm profile sampled. Therefore, even if S has accumulated deeper in the profile (>30 cm) it is likely to be below the root zone of most annual species until late in the growing season. Our results indicate nutrient stratification may limit pasture production more than pH stratification in the ACT.

Key Words
Soil testing, stratification, soil acidity, nutrient imbalance

Introduction
Soil pH and nutrient availability are important drivers of pasture and crop production, with strongly acidic or strongly alkaline soil influencing the availability of key nutrients to plants. Recent field surveys in south eastern Australia have indicated soil acidity coupled with disparity in availability of key nutrients; excess phosphorus (P) and inadequate sulfur (S), may be a significant constraint to the productivity of extensive dryland legume-based pastures (Hackney et al. 2019). Soil pH can also inhibit root growth and development thereby limiting acquisition of nutrients and moisture, particularly under acidic soil conditions where high levels of aluminium (Al) become available (Helyar et al. 1991). Additionally, legume root-nodule formation and symbiosis may be limited by low pH and presence of Al (Helyar et al. 1991). Previous research has shown nutrient and pH stratification with depth is often exacerbated by management, including nitrogen (N) fertiliser use in cropping systems and/or nitrate leaching from annual legume-dominant pastures (Evans et al. 1998; Dear et al. 2009; Ryan et al. 2017). Specifically, much of the nutrient stratification research in soils has focussed on P in dairy systems (predominately 0-10 cm soil layer) and the potential of P-enriched soil to move into waterways and contribute to eutrophication (Dougherty et al. 2006; Ryan et al. 2017). Similarly, research on pH stratification in south eastern Australia has occurred in the mixed farming zone either under cropping systems focussing on finer depth sampling increments within the 0-10 cm or 0-20 cm soil layers (Evans et al. 1998; Burns et al. 2017) or under phase pastures in the cropping rotation (0-12 cm; Dear et al. 2009), with little information under permanent pastures. This study examined whether soil pH and nutrient stratification occurred in pasture or crop paddocks in the ACT and discusses the implications for pasture production.

Methods
Twenty-three paddocks on 12 commercial grazing properties were sampled in Spring 2018. Sites were selected by way of an expression of interest from landholders involved in ACT Government land management extension programs. Landholders were asked to identify up to two paddocks for which they had detailed management history (data not presented). Paddocks ranged from native-based perennial grasses [either red grass (*Bothriochloa macra*), kangaroo grass (*Themeda triandra*), weeping grass (*Microlaena stipoides*) or *Poa* spp.] to pastures containing introduced phalaris (*Phalaris aquatica*) or lucerne (*Medicago sativa*) and oat (*Avena sativa*) fodder crops. Within each paddock, a representative area of 40 m x 40 m was selected for soil sampling. Sixteen soil cores were collected using a hydraulic corer to a depth of at least 30 cm, with a 40 mm inner diameter coring tube. Composite samples were made for the 0-5, 5-10, 10-20 and 20-30 cm soil layers. Soil chemical analysis was performed at the Nutrient Advantage Laboratory (Werribee, Victoria) with methods

following Rayment and Lyons (2011). Briefly, soil samples were oven dried at 40°C, sieved to 2 mm and analysed for: pH $CaCl_2$ (Method 4B2), Phosphorus - Colwell (Method 9B2; 0-5 cm and 5-10 cm only), phosphorus buffering index (PBI; Method 9I2b; 0-5 cm and 5-10 cm only), available sulphur (KCl-40 extraction; Method 10D1), available potassium (18A1; 0-5 cm and 5-10 cm only), exchangeable cations including cation exchange capacity (Methods 15D3 and 15J1) and total carbon and total nitrogen (6B2b and 7A5). Results of soil nutrient analysis were statistically analysed using REML (Genstat 19th Edition), with depth as a fixed effect and site (paddock) as the random effect. An index was developed for soil parameters by comparing, within individual paddocks, the surface soil (0 to 5 cm) analysis value with the other depths. In this way, the extent of stratification was compared on the same basis across sites.

Results

Forty-eight percent of paddocks sampled had pH_{Ca}<5.0 in the 0 to 5 cm soil with one-third of these paddocks having the remainder of the depth profile as more acidic (but none by more than 0.2 pH_{Ca} units). There was no statistical evidence (*P*=0.18) of pH stratification in the paddocks sampled (Table 1). Conversely, P was strongly stratified with the 0 to 5 cm depth, a layer with double the amount in the 5 to 10 cm depth (Table 1). Sixty six percent of paddocks had available P greater than the critical level in the 0 to 10 cm soil layer. Potassium was also strongly stratified with the K content of the 5-10 cm depth only 64% of the 0-5 cm soil layer (Table 1). Ninety two percent of paddocks had available Col K>Critical in the 0-10 cm layer. Sulphur was strongly stratified and decreased with depth with the 20 to 30 cm depth being only 37 % of the 0 to 5 cm soil layer (Table 1). Sixty one percent of paddocks were deficient in S (<8 mg/kg; Gourley et al. 2007) in the 0-10 cm soil layer while 61 % of paddocks were deficient throughout the entire 0-30 cm soil layer sampled. As expected, total C and N concentration was significantly higher in the surface 0 to 5 cm of soil compared with the other soil layers and decreased in concentration with depth. There was no significant difference in the C:N ratio in the 0 to 20 cm soil layers; however, it was significantly lower in the 20 to 30 cm soil (mean 8.8, Table 1).

Table 1. Mean nutrient and index values for soil sampled from 23 pasture paddocks in the ACT and analysed for: soil pH ($CaCl_2$), available phosphorus (P Colwell), available potassium (K Colwell), available sulphur (S KCl40), total carbon (Total C - LECO) and total nitrogen (Total N - LECO).

Soil characteristic	Soil depth (cm)					LSD	P-value
	0-10	0-5	5-10	10-20	20-30		
pH index		1.00	0.98	0.99	1.03	0.046	0.18
pH_{Ca}	5.2	5.2	5.1	5.1	5.3	0.32	0.52
Available P index		1.00	0.50			0.16	<0.001
P (Colwell) (mg/kg)	36.1	49.1	23.1			22	0.025
K index		1	0.64			0.13	<0.001
K (Colwell) (mg/kg)	267	334	210			80	0.003
Available S index		1.00	0.89	0.66	0.37	0.13	<0.001
S (KCl-40) (mg/kg)	8.5	9.2	7.9	5.6	2.9	3	<0.001
Total C-index		1.00	0.59	0.34	0.19	0.076	<0.001
Total C (%)	2.4	3.1	1.8	1.0	0.56	0.36	<0.001
N-index		1.00	0.60	0.36	0.25	0.072	<0.001
Total N (%)	0.2	0.26	0.15	0.088	0.061	0.028	<0.001
C:N	12.4	12.0	12.0	11.4	8.8	1.22	<0.001

Discussion

In contrast to previous studies (Evans et al. 1998; Burns et al. 2017; Ryan et al. 2017), there was no evidence of soil pH stratification under the pastures observed in this study. Where pH stratification has been reported, it has been under crops (Evans et al. 1998; Burns et al. 2017) or annual pasture systems (Ryan et al. 2017) where nitrate leaching was identified as a key cause of stratification. In the mixed farming zone of NSW, Dear et al. (2009) reported significantly lower rates of nitrate leaching under pasture swards consisting of perennial grasses and annual legumes compared with annual legume pasture phases due to nitrate utilisation by the perennial grasses. In our study, there are several possible explanations for the absence of pH stratification, including the minimisation of nitrate leaching due to utilisation by the perennial grasses. However, this does not explain why the pH in the surface 0-5 cm soil layer is not higher than the next layer (i.e. 5-10 cm) as OM return to the soil surface and the subsequent alkaline decomposition should create a more alkaline surface soil (Evan et al 1998, Paul et al. 2001). Adequate rates of lime incorporated into the surface 0-10 cm soil could remove soil pH stratification but management data collected as part of this field survey (data not presented) indicates that where lime has been used it was infrequent (typically every 5-10 years), at low rates (<2.5t/ha) and top-dressed. Hence, stratification would still be expected to be evident in the soil profiles. A likely possibility is that stratification is occurring, but it is within the surface 0 to 5 cm soil layer and therefore finer depth increments may be warranted to detect strongly acidic layers.

The P stratification observed in our study agrees with other studies on annual pastures (e.g. Ryan et al. 2017). It was reported by Ryan et al. (2017) that strong stratification of K in texture contrast soils in WA, with S-stratification also apparent but less pronounced than for K. In our study, S was strongly stratified and showed no indication of accumulation in any soil layer to 30 cm, with more than 60% of paddocks being deficient in S. Increasingly, producers are moving away from single superphosphate to higher analysis P-fertilisers at the expense of S, and are advised that there is no need to apply S when surface soil layers (0 to 10 cm) are deficient as S is likely to be present at depth. Our results indicate that there is no S accumulation to 30 cm, and if in fact S is accumulating deeper than 30 cm, then it is likely to be beyond the access of shallower-rooted plant species (e.g. subterranean clover) and may be limiting pasture productivity and N-fixation (Varin et al. 2010).

The pattern of TC and TN concentration was consistent with other tableland field surveys under pastures in south eastern Australia (Orgill et al. 2014 and 2017); with the greatest concentration of TC and TN in the surface soil (0 to 5 cm) coinciding with high organic matter accumulation from plants and animals and the zone of maximum soil biological activity, and decreasing contents with depth. Interestingly, the significantly lower C:N ratio (mean 8.8) in the 20 to 30 cm soil indicates an accumulation of stable soil organic carbon (Kirkby et al. 2011).

Our field survey suggests that nutrient availability and particularly the disparity in availability of P, S and possibly K may be of greater concern than soil pH stratification in the ACT. Despite soil pH stratification not being identified as an issue for the sites surveyed in this study, our findings support the notion of revised soil sampling protocols to better understand soil chemistry in the surface (0 to 5 cm, 5 to 10 cm) and subsurface (10 to 20 cm, 20 to 30 cm) soil layers. These protocols are likely to be increasingly important under permanent pastures and in no tillage systems where applications of nutrients and ameliorants (e.g. lime) occur on the soil surface. Management should focus on the maintenance soil pH_{Ca} at or above 5.0, and preferably 5.5 for optimal performance of key grass and legume species used in ACT pastures, and to avoid the acidification of surface soil. An opportunity exists to reduce P application, and potentially focus on S given that over 60% of paddocks surveyed had P above critical levels, while a similar proportion of paddocks were deficient in S. Moreover, the assumption of S-accumulation at depth may require review.

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