The resilience of soil organic carbon stocks under contrasting hill country pasture management practices

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Abstract
In 2020 we measured the stability of soil organic carbon (SOC) concentrations and stocks under contrasting hill country pasture regimes, by sampling three slope classes and three aspect locations on each of three farmlets of a long-term phosphorus fertiliser and sheep grazing experiment. The farmlets included no annual phosphorus (NF), 125 kg of single superphosphate/ha (LF), or 375 kg superphosphate/ha (HF) that has been applied on an annual basis since 1980. Results from the 2020 sampling event were added to previous results reported from soil samples collected in 2003 and 2014. The SOC concentrations in the topsoil (0-75 mm depth), ranging from 4.23 to 5.99% across all slopes and aspects of the farmlets, fell within the normal range (≥ 3.5 and < 7.0%) required for sustaining production and environmental goals. A trend was shown for greater SOC stocks in the topsoil in the HF farmlet (34.0 Mg/ha) compared with the other two farmlets (31.6 Mg/ha), but this trend was not evident in the deeper soil layers (75-150, 150-300, 0-300 mm). Under the current conditions, topographical features such as slope and aspect had a more profound influence on SOC stocks than management history.

Keywords: grasslands, long-term experiment, phosphorus fertiliser, sheep grazing

Introduction
A resilient pastoral system is dependent on sustaining the underlying soil resource, including sufficient organic matter (OM) for aggregate building, underpinning soil physical structure and water storage, and as a source of nutrients for plant growth and sustainment of the biological community. Sparling et al. (2008) developed a set of provisional quality classes and target ranges for soil organic carbon (SOC) concentration in topsoil (0-75 mm) of pastoral systems for sustaining both production and environmental goals. Because soils differ in the amounts of SOC they contain, due to differences in mineralogy and climate, SOC concentration targets for sustaining soil quality are divided into three distinct groups that include (i) semi-arid, pumice and recent soils, (ii) allophanic soils and (iii) all other soils excluding organic soils (Sparling et al. 2008). Knowledge of what the SOC concentrations are in the topsoil of our pastoral systems, along with an understanding of the impact of current practices, is becoming increasingly important. To that end, improving SOC and resilience (while minimising soil loss) to sustain a productive sector well into the future, is one of the four goals of the Beef + Lamb New Zealand Environment Strategy and Implementation Plan launched in 2018 (https://beeflambnz.com/sites/default/files/levies/files/Env-Strategy-1yr-rep%28v2%29.pdf). Carbon (C) is also rapidly becoming a second currency that we need to consider in our on-farm decision making, because the organic C stored in soil OM is a significant reservoir within the global C cycle and hence critical in climate regulation.

Long-term grazing experiments on permanent pastures assessing the effect of phosphorus (P) fertilisation (and associated effects on pasture production and livestock carrying capacity) on SOC concentrations and stocks provide a rare opportunity to examine trends over time. These experiments have shown differing results; some studies show either no or minimal differences in SOC concentrations and stocks under varying sustained P inputs (Cayley et al. 2002; Schipper et al. 2011; Condron et al. 2012; Young et al. 2016) whereas other studies show an increase in these variables with a higher sustained P input (Chan et al. 2010; Coonan et al. 2019). The absence of a significant accumulation of SOC in response to increased production in the former group was mostly attributed to faster decomposition of OM inputs associated with a combination of improved pasture quality and increased earthworm activity. Beyond native soil fertility and climate contributing to fluctuating C turnover rates, the reasons for these variations are often poorly understood (McSherry & Ritchie 2013; Stiles et al. 2018).

Both slope and aspect play an important role in SOC dynamics and storage; these features temper precipitation and infiltration, water flows and pathways (Zhong et al. 2016), and modulate animal grazing and excretal behaviour (López et al. 2003; Betteridge et al. 2010). The net transfer of nutrients in excreta contributes to soil fertility on the micro-topographies present in the

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complex landscapes of the North Island hill country (Hoogendoorn et al. 2016). In 2020 we measured SOC concentrations and stocks of the long-term P fertiliser and sheep stocking regimes (herein ’*farmlet*‘ effects) located at the Ballantrae, AgResearch Hill Country Research Station, to add to results from previous soil sampling events (2003 and 2014) published elsewhere (Mackay et al. 2018; 2021). In this study, an additional sampling event conducted in 2020 (to a 300-mm depth) allowed for a direct comparison with 2003 data on the deepest soil sampling layer (150-300 mm), and to confirm the SOC trends seen earlier in the analysis of 2003 and 2014 sampling events (Mackay et al. 2018; 2021).

Materials and Methods

Study site

The study was conducted at Ballantrae in Southern Hawke’s Bay. The characteristics of the Research Station and the three self-contained experimental farmlets under varying single superphosphate fertiliser regimes and grazing sheep stocking rates established in 1975, are described in detail in Mackay et al. (2021).

Grazing Livestock

Breeding ewes have been grazing the farmlets in a rotational fashion since 1975. Before then, these farmlets had carried about 6.0 stock units (SU)/ha (herein, 1 SU is equal to 550 kg of dry matter (DM), the annual consumption of a 55-kg breeding ewe plus a single lamb, Woodford & Nicol 2004). Farmlets were stocked to maintain similar grazing pressures across farmlets (i.e., a similar number of SU per unit of pasture herbage produced). Over the 1980-2014 period, mean annual stocking rates were 6.9, 9.8 and 15.9 SU/ha (NF, LF and HF farmlets, respectively; corresponding annual pasture yields during the 2015-2016 season were 6917, 9708 and 11289 kg DM/ha (Mackay & Costall 2016).

Soil sampling

Soil samples were collected from three farmlets receiving varying amounts of annually applied P fertiliser, as described in Mackay et al. (2021). On these farmlets, soils were sampled to a 300-mm depth (0-75, 75-150 and 150-300 mm) in 2003 and in 2020, and to a 150-mm depth (0-75, 75-150 mm) in 2014. Within each farmlet, soil samples were collected from 18 permanently-marked sites (in place since 1975) that represent the predominant topographical features of these farmlets (Lambert et al. 2014). The permanent sites include three slope classes [low slope (LS; 1-12°), medium slope (MS; 13-25°), and high slope (HS; >25°)] and three aspect locations grouped relative to the true north [east (E; 35 - 155°), southwest (SW; 155 - 275°), and northwest (NW; 275 - 35°)]. At each of the 54 sites, 20 soil cores (25 mm diameter) were collected and bulked for total soil C and P concentration analysis, and a separate set of soil samples were collected using intact stainless-steel rings (100 mm diameter) at each depth to determine bulk density (BD). Soil sampling protocol and sample preparation, and subsequent analysis, are described in Mackay et al. (2021).

At each sampling site (*i*) and soil depth increment (*Dij*, in mm), SOC stock estimates (expressed as Mg C/ha) were obtained from soil C concentration (% or Mg C/100 Mg soil) and *BD* (Mg/m^3) according to the following equation:

$$SOC\ stocks_{ij} = \frac{C\ concentration_i}{100} \times BD_{ij} \times D_{ij}\ \times 10$$

Statistical analysis

The effects of farmlet, slope class and aspect location (‘*site*’ effect), and sampling year on soil BD, N and C concentration, C:N ratio, and C stocks were analysed according to a split-split-plot design. Farmlet, site and year of sampling represent the main plot, split-plot and split-split plot, respectively. Slope class (three levels) and aspect location (three levels) combinations were represented twice within each farmlet (n = 18 sites per farmlet). Analyses were conducted using GenStat 20th edition (VSN International 2020). Means are significantly different at P≤0.05 (with smaller values providing stronger evidence for significance) and P-values >0.05 but ≤0.10 are considered a trend.

Results

Year effects

There were significant differences in BD, SOC (%) and N (%), leading to variation in SOC stocks in the topsoil between years (Table 1). Year of sampling only affected BD and SOC stocks in the following soil depth (75-150 mm) and had no effect on the soil characteristics in the third depth (150-300 mm) or when all three depths (0-300 mm) were combined (Table 1). Estimates of SOC stocks decreased (P=0.02) from 2003 (32.8 Mg/ha) to 2014 (31.4 Mg/ha), but the former was similar to that of 2020 (33.0 Mg/ha) in the topsoil. These differences were reversed in the second soil depth (75-150 mm, Table 1).

Farmlet effects

There was a trend for greater SOC concentration (5.4%) and stocks (34.0 Mg/ha) under the HF farmlet in the topsoil compared with the other two farmlets (5.1% and 31.6 Mg/ha, respectively), but this trend was not evident for the deeper soil layers (Table 1). Accumulated SOC stocks (0-300 mm) were similar across farmlets (111.1, 109.8 and 111.5 Mg C/ha for the NF, LF, and HF farmlets, respectively, Table 1).

Table 1 Sampling year, farmlet (phosphorus fertiliser and associated sheep stocking rate) and topographical feature (slope class and aspect location), and soil bulk density (BD; Mg/m³), nitrogen (N) and carbon (C) concentration (%), and C stocks (Mg C/ha) at Ballantrae Hill Country Research Station. Pooled data from sampling years (2003, 2014 and 2020) at each soil depth (0-75, 75-150, and 150-300 mm) are included.

Variables by soil depth	Year (Y)[1]			Farmlet (F)[2]			Slope (S)[3]			Aspect (A)[4]			s.e.m[5]	s.e.m[6]
	2003	2014	2020	NF	LF	HF	LS	MS	HS	E	NW	SW		
0-75 mm														
BD (Mg/m³)	0.79^{a}	0.87^{b}	0.89^{b}	0.86	0.84	0.85	0.80^{a}	0.85^{b}	0.92^{c}	0.82^{a}	0.90^{b}	0.84^{a}	0.009	0.016
C (%)	5.62^{a}	4.92^{b}	5.10^{b}	5.14	5.10	5.40	5.99^{a}	5.41^{b}	4.23^{c}	5.52^{a}	4.67^{b}	5.45^{a}	0.077	0.190
N (%)	0.44^{a}	0.40^{b}	0.39^{b}	0.40	0.40	0.44	0.50^{a}	0.43^{b}	0.32^{c}	0.45^{a}	0.37^{b}	0.43^{a}	0.007	0.017
C:N ratio	12.9^{a}	12.4^{b}	13.0^{a}	13.1	12.9	12.3	12.1^{a}	12.8^{b}	13.3^{b}	12.4	12.9	12.9	0.08	0.22
C stocks (Mg/ha)	32.8^{a}	31.4^{b}	33.0^{a}	31.6	31.7	34.0	34.6^{a}	34.0^{a}	28.7^{b}	32.9	31.0	33.4	0.42	0.80
75-150 mm														
BD (Mg/m³)	0.97^{a}	1.07^{b}	1.06^{b}	1.03	1.06	1.01	1.00^{a}	1.03^{a}	1.07^{b}	1.02^{a}	1.08^{b}	1.00^{a}	0.010	0.014
C (%)	3.91	3.97	3.85	3.99	3.79	3.96	4.35^{a}	4.14^{a}	3.24^{b}	4.10^{a}	3.27^{b}	4.36^{a}	0.053	0.162
N (%)	0.31	0.32	0.31	0.32	0.30	0.32	0.37^{a}	0.33^{b}	0.25^{c}	0.34^{a}	0.26^{b}	0.35^{a}	0.005	0.012
C:N ratio	12.6	12.3	12.5	12.5	12.5	12.4	11.8^{a}	12.6^{b}	12.9^{b}	12.1	12.5	12.7	0.08	0.25
C stocks (Mg/ha)	28.5^{a}	31.3^{b}	29.9^{c}	30.2	29.7	29.8	32.2^{a}	31.6^{a}	25.9^{b}	31.0^{a}	26.2^{b}	32.4^{a}	0.46	0.99
Accumulated C stocks (Mg/ha)[7]	61.3	62.7	62.8	61.7	61.3	63.8	66.8^{a}	65.5^{a}	54.5^{b}	63.9^{a}	57.1^{b}	65.9^{a}	0.72	1.72
150-300 mm														
BD (Mg/m³)[8]	1.20	-	1.16	1.19	1.19	1.17	1.16	1.18	1.20	1.17	1.24	1.13	0.013	0.016
C (%)	2.76	-	2.81	2.88	2.75	2.73	3.08^{a}	2.95^{a}	2.34^{b}	2.85^{a}	2.25^{b}	3.26^{c}	0.039	0.136
N (%)	0.22	-	0.23	0.24	0.22	0.21	0.25^{a}	0.23^{a}	0.18^{b}	0.24^{a}	0.18^{b}	0.25^{a}	0.003	0.010
C:N ratio	12.6	-	12.6	12.4	12.6	12.7	12.0	12.8	12.9	12.2	12.5	12.9	0.09	0.27
C stocks (Mg/ha)	49.7	-	47.7	50.2	48.6	47.3	52.5^{a}	51.8^{a}	41.9^{b}	49.7^{a}	41.4^{b}	55.1^{a}	0.83	2.01
Accumulated C stocks (Mg/ha)[7]	111.0	-	110.6	111.1	109.8	111.5	118.5^{a}	117.7^{a}	96.3^{b}	113.3^{a}	98.4^{b}	120.7^{a}	1.31	3.50

[1] Year: Year of sampling.
[2] Farmlet: NF: no annual P, LF: 125 kg single superphosphate (SSP)/ha, HF: 375 kg SSP/ha, applied on an annual basis since 1980.
[3] Slope: Low slope (LS): 1-12°, medium slope (MS): 13 - 25°, high slope (HS): >25°.
[4] Aspect: East (E): 35 - 155°, northwest (NW): 155 - 275°, southwest (SW): 275 - 35°, degrees relative to the true north.
[5] Standard error of the mean for Y.
[6] Standard error of the mean for F, S, and A.
[7] Accumulated to the specified maximum depth.
[8] A BD value of 1.2 Mg/m³ was assumed for 2003 (from Lambert et al. 2000).
[a,b,c] Within each main factor (Y, F, S, A) and soil variable, numbers with different superscripts differ ($P \leq 0.05$).

Slope effects

Slope class had a strong influence on all soil characteristics leading to variation in SOC concentration and stock estimates as most variables differed (P<0.05) between the three slope classes at all soil depths (Table 1). Compared with soil samples collected from the low and medium slope classes, samples from the steepest slope class (>25°) had a higher BD, wider C:N ratios, and lower N and C concentrations, and lower SOC stocks at all soil depths (Table 1).

Aspect effects

Except for C:N ratios (and SOC stocks in the topsoil), aspect location, like slope, had a strong influence on soil properties, with most variables differing (P<0.05) between the three aspect locations at all soil depths (Table 1). Soil samples collected on the NW-facing slopes resulted in higher BD, and lower N and C concentrations, and SOC stocks, compared with samples collected at the other two aspect locations (Table 1).

Discussion

Except for numerical differences in the topsoil, the varying P fertiliser and stocking regimes across farmlets had a minimal impact on SOC stocks at greater depths (75-150, 150-300, 0-150 and 0-300 mm). The SOC data from the 2020 sampling added to earlier findings from soil sampling events (Lambert et al. 2000; Mackay et al. 2021) providing further evidence of the stability of SOC concentrations and stocks under permanent pastures varying markedly in soil P fertility and associated livestock production.

The NF farmlet represents a low fertility system with low levels of pasture and animal production, while the HF farmlet appears at the other end of the soil fertility and production spectrum (Figure 1). Our findings support earlier findings from other long-term studies in New Zealand (Condron et al. 2012) and overseas (Cayley et al. 2002; Young et al. 2016). Further, based on the findings from this study site (Figure 2) and Schipper et al. (2011) from another long-term fertiliser trial on hill country, the soil OM pool size under permanent pastures managed with varying P fertiliser regimes fluctuates over time, seemingly without a clear long-term trend. These management regimes embrace the range of soil fertility and sheep stocking rates found in most New Zealand hill country systems.

The SOC concentrations in the topsoil (farmlet means ranged from 5.1 to 5.4%) were well within the normal range (≥ 3.5 and < 7%) defined by Sparling et al. (2008) for sustaining production and environmental goals. At these concentrations the soils are well buffered, with small fluctuations in SOC likely to have small effects on the performance and resilience of the pastoral system. Even on the steepest slope class, where SOC concentrations were lower (4.23%) than the other two slope classes (5.7%), these values were still within the normal range, well above the threshold that would have placed them in either the depleted (≥ 2.5 and < 3.5%), or very depleted (<2.5%) range.

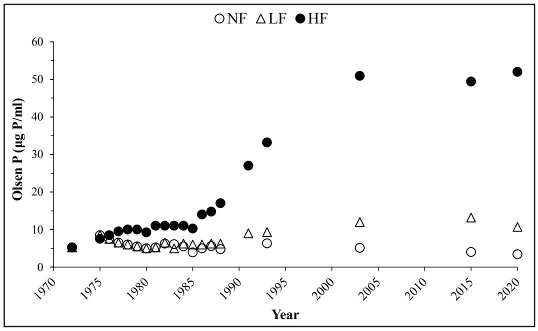

Figure 1 Soil Olsen P values (µg/ml) at the Ballantrae Hill Country Research Station over time. Farmlets: NF = no annual P applied, LF = 125 kg single superphosphate (SSP)/ha, HF = 375 kg SSP/ha, applied on an annual basis since 1980. Data prior to 2003 were provided by Lambert et al. (2000). Each data point represents the mean value of 18 sampling sites.

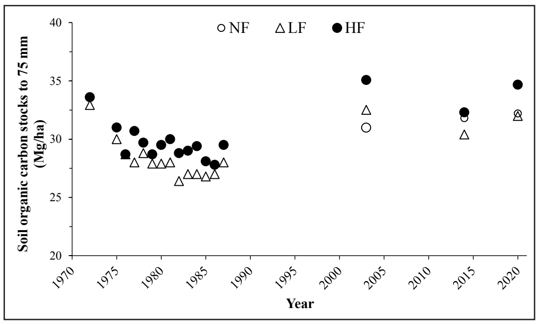

Figure 2 Soil C stocks (Mg C/ha) within 0-75 mm depth on the NF, LF and HF farmlets since 1972. Farmlets: NF = no annual P applied, LF = 125 kg single superphosphate (SSP)/ha, HF = 375 kg SSP/ha, applied on an annual basis since 1980. Data prior to 2003 were provided by Lambert et al. (2000). Data from Lambert et al. (2000) were from all 10 farmlets at Ballantrae, whereas the findings in 2003, 2014 and 2020 are from only three of those farmlets (see text for more detail).

Data on the distribution of SOC concentrations in pastoral systems, as influenced by slope and aspect, provide invaluable insights that can assist with the sampling of SOC concentrations and stocks in complex landscapes. In our study, for example, mean values obtained from the medium slope class, accounting for any major aspect differences, appear to be representative of all three slope classes. In cases where this slope class is also representative of soil fertility trends across slopes (i.e., Morton et al. 2000), soil samples collected for monitoring soil fertility could also be used for monitoring SOC concentrations. This becomes increasingly relevant as the pressure to extend the monitoring of our soil resource beyond chemical fertility to include a measure of OM, physical condition, and biological activity to assess overall health increases. Current research is using data from the long-term P fertiliser and sheep grazing experiment to develop a protocol for assessing soil health in hill country pastures as part of the Hill Country Futures programme (https://beeflambnz.com/hillcountryfutures).

The long-term experiment allowed for a comprehensive assessment of the influence of contrasting P fertiliser and associated sheep stocking rate on SOC concentrations and stocks in the underlying soil resource. The additional sampling event in this study (to a 300-mm depth in 2020) allowed for (i) an augmentation of data beyond that of Mackay et al. (2018; 2021), (ii) a direct comparison with 2003 data on the deepest soil sampling layer (150-300 mm), and (iii) an overall confirmation of findings reported elsewhere (Mackay et al. 2018; 2021).

Implications

This study examined SOC concentrations and stocks under a long-term P fertiliser and sheep grazing experiment in hill country that has been running since 1975. Soil samples collected on the steepest slope class and on NW-facing slopes had lower SOC concentrations and stocks, compared with samples collected from the other two slope classes and aspect locations. Across the three distinct farmlets, SOC pool sizes have remained stable indicating that despite the range of pasture management regimes, the underlying soil resource is being sustained for livestock production, along with a wider range of other services.

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