Soil Carbon Stocks Are Stable under New Zealand Hill Country Pastures with Contrasting Phosphorus and Sheep Stocking Regimes

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The XXIV International Grassland Congress / XI International Rangeland Congress (Sustainable Use of Grassland and Rangeland Resources for Improved Livelihoods) takes place virtually from October 25 through October 29, 2021.
Proceedings edited by the National Organizing Committee of 2021 IGC/IRC Congress
Published by the Kenya Agricultural and Livestock Research Organization

Presenter Information

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Key words: Soil carbon stocks; pastures; phosphorus fertiliser; sheep grazing; long-term experiment.

Abstract

A temporal and spatial assessment is required to quantify the effects of nutrient inputs and varying grazing management regimes on soil organic carbon (SOC) stocks under grazed pastures in complex landscapes. We examined SOC stocks under permanent pastures in three farmlets under a range of different annual phosphorus (P) fertiliser and associated sheep stocking regimes. The farmlets examined had either no annual P applied (NF), 125 kg single superphosphate (SSP) ha^{-1} (LF), or 375 kg SSP ha^{-1} (HF) on an annual basis since 1980. Soils were sampled to three depths (0-75, 75-150, 150-300 mm) in 2003 and 2020, and to the two upper depths in 2014. Each farmlet included three slope classes [low slope (LS), medium slope (MS), high slope (HS)], on three different aspect locations [east (E), southwest (SW), northwest (NW)]. Although a trend ($P = 0.07$) was observed for greater SOC stocks in the upper depth of the HF farmlet (34.0 Mg C ha^{-1}) compared with the other two farmlets (31.6 Mg C ha^{-1}), this trend was discontinued in deeper layers. Accumulated SOC stocks (0-300 mm) were 111.1 (NF), 109.8 (LF) and 111.5 (HF) Mg C ha^{-1}. Soil samples collected on HS resulted in higher soil bulk densities (BD) and carbon-to-nitrogen (C:N) ratios, and lower C concentration and SOC stocks, compared with samples collected on the other two slope classes. Soil samples collected on the NW-facing slopes resulted in higher BD, and lower C concentration and SOC stocks, compared with samples collected on the other two aspect locations. Under the current conditions, contrasting P fertiliser and sheep stocking regimes had minimal effects on SOC stocks. In contrast, topographic features had major effects on SOC stocks, and need to be considered in soil sampling protocols that monitor soil organic carbon stocks over space and time.

Introduction

Studies on long-term phosphorus (P) fertilisation (and associated effects on pasture production and livestock carrying capacity) and soil organic C (SOC) stocks under permanent pastures have shown contrasting results (Condron et al. 2012; Schipper et al. 2013; Young et al. 2016; Coonan et al. 2019; Mackay et al. 2021). A higher sustained P input (and corresponding pasture production) resulted in higher long-term soil C sequestration compared with a no P system (Coonan et al. 2019). In contrast, despite higher annual net primary production (1.9 to 3.6 Mg C ha^{-1}) from a high- compared with a low-fertility system (the latter with about half the rate of a P-based fertiliser applied over a twenty-year period), soil C stocks were similar (Young et al. 2016). Other than inferred varying C turnover rates, the reasons behind these outcomes are often poorly understood (McSherry and Ritchie 2013).

Previously, Lambert et al. (2000) reported similar SOC stocks in repeatedly sampled pastoral soils under varying P fertiliser regimes (and associated sheep stocking rates) to a depth of 75 mm from 1972 to 1987, at the Ballantrae long-term P fertiliser and sheep grazing study (1972-present). Adding the latter findings to more recent measures from three of the original 10 farmlets, provided a time series (1980-2014) that supports the view that soil C stocks are relatively stable under permanent pastures managed under those conditions (Mackay et al. 2021). The objective of this study was to update (and potentially extend) this view; we examined the effect of long-term contrasting P fertiliser and sheep stocking regimes (herein farmlet effects) and topographical features on SOC stocks under a topographically diverse grassland that is representative of New Zealand's North Island grazing hill country.

Methods and Study Site

The study was conducted at AgResearch's Ballantrae Hill Country Research Station, in Southern Hawke's Bay (40.8180° S; 175.8500° E). The Research Station is 300 m.a.s.l. with an average air temperature of 12.8ºC and an annual rainfall of 1270 mm. Soils are classified as Brown and Pallic soils (Hewitt, 1998) (Andic Distrochrepts, Typic Distrochrepts and Typic Eutrochrepts in the USDA Classification).

The three self-contained experimental farmlets examined in this study have been under different single superphosphate (SSP; approximately 9% P, 11% S) fertiliser regimes and grazing sheep stocking rates since

1975. Prior to 1975, SSP was applied to the whole site at a rate of 250 kg ha^{-1} in 1973 and again in 1974. We sampled three farmlets (Mackay et al. 2021): NF (9.7 ha) = no annual P applied, LF (8.1 ha) = 125 kg SSP ha^{-1} and HF (6.8 ha) = 375 kg SSP ha^{-1}, on an annual basis since 1980. On each of the three 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, as described in Mackay et al. (2021). Farmlets include three slope gradient ranges, herein referred to as slope classes [low slope (LS; 1-12°), medium slope (MS; 13-25°), and high slope class (HS; >25°)], on three different aspect locations grouped relative to the true north [east (E; 35-155°), southwest (SW; 275-35°), and northwest (NW: 155-275°)].

Breeding ewes have been rotationally grazing the farmlets since 1975. Prior to 1975, these farmlets had been carrying about 6.0 stock units (SU) ha^{-1} (1 SU is defined as a 55-kg breeding-ewe-plus-single lamb consuming 550 kg dry matter (DM) per year). Farmlets were stocked to maintain a similar grazing pressure across farmlets (i.e., similar SU per unit of pasture production). Mean annual stocking rates over the period 1980 – 2014 were 6.9 (NF), 9.8 (LF), and 15.9 (HF) SU ha^{-1}. Corresponding estimates of annual pasture production during the 2015 - 2016 season were 6917, 9708 and 11289 kg DM ha^{-1} (Mackay and Costall 2016). The effect of farmlet, topographical feature (slope class and aspect location) and sampling year (and their multiple interactions) on soil BD, N and C concentration, C:N ratio, and C stocks were subject to analysis of variance according to a split-split-plot design (Mackay et al. 2021).

Results

Soil organic carbon stocks – Year and farmlet effects

Year of sampling had a significant effect on all soil characteristics leading to SOC stock estimates in the upper depth (0-75 mm), and affected BD and SOC stocks in the following soil depth layer (75-150 mm) (Table 1). Estimates of SOC stocks decreased ($P = 0.02$) from 2003 (32.8 Mg ha^{-1}) to 2014 (31.4 Mg ha^{-1}), but the former were similar to those in 2020 (33.0 Mg ha^{-1}) in the upper soil depth (0-75 mm). Accumulated SOC stocks (0-150 mm and 0-300 mm) were not affected by year of sampling (Table 1). Farmlets had minimal effects on soil characteristics (Table 1). A year-by-farmlet interaction trend on SOC stocks for the upper depth ($P = 0.07$) was most likely associated with numerical differences in SOC stocks in 2003 and 2020, but not in 2014. This trend was not seen in the deeper (75-150 and 150-300 mm) and cumulative (0-150 and 0-300 mm) soil layers (Table 1).

Soil organic carbon stocks – Slope and aspect effects

Slope class had a strong influence on all soil characteristics leading to SOC stock estimates as most variables differed ($P < 0.05$) between the three slope classes at all soil depths (Table 1). Overall, soil samples collected on the steepest slope class (>25°) resulted in lower SOC stocks at all soil depths, compared with samples collected at the other two slope classes (Table 1). Except for C:N ratios and SOC stocks in the upper depth, aspect location had a strong influence on soil characteristics as most variables differed ($P < 0.05$) between the three aspect locations at all soil depths (Table 1). Overall, soil samples collected on the NW-facing slopes resulted in higher BD, and lower N and C concentration, and SOC stocks at all soil depths, compared with samples collected at the other two aspect locations (Table 1).

Discussion [Conclusions/Implications]

The farmlet without P fertiliser for the last 40 years prior to 2020 (NF) represents a low fertility (Olsen P = 3.4 µg ml^{-1}; 0-75 mm), extensive temperate pastoral livestock system carrying about 6 SU ha^{-1} with pastures dominated by low fertility grasses and few legumes. In sharp contrast, the farmlet that received P fertiliser inputs above annual maintenance requirements since 1975 (HF) represents a high fertility soil (Olsen P = 52 µg ml^{-1}) intensive hill land livestock system (16 SU ha^{-1}).

Despite ongoing divergence in pasture growth, pasture composition and livestock performance (Lambert et al. 2014) and in chemical and biological characteristics of the soils (Lambert et al. 2000; Parfitt et al. 2010; Schon et al. 2019) the contrasting management regimes (farmlets) had a minimal influence on SOC stocks. These findings seem to contradict those of a review by Conant et al. (2001) that reported that both fertiliser and improved grazing management tend to increase SOC stocks. However, increases in annual rates of C sequestration from changes in grazing management and fertilisation reported by Conant et al. (2001) were minimal compared with other management practices such as conversion from cultivation, introduction of earthworms and irrigation.

Table 1. The effect of year of sampling, farmlet (P fertiliser and associated sheep stocking rate) and topographical feature (slope class and aspect location), on soil bulk density (BD; Mg m^{-3}), nitrogen (N) and carbon (C) concentration (%), and C stocks (Mg C ha^{-1}) at the Ballantrae Hill Country Research Station.

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 m^{-3})	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^{-1})	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 m^{-3})	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^{-1})	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
C stocks (Mg ha^{-1})[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 m^{-3})[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^{-1})	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
C stocks (Mg ha^{-1})[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^{-1}, HF: 375 kg SSP ha^{-1}, 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 m^{-3} 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 ($P \leq 0.05$).

Findings from our study, however, are consistent with those of Lambert et al. (2000) who reported that varying P fertiliser inputs and sheep grazing regimes did not influence SOC stocks in the 0-75 mm soil depth on the LF and HF farmlets. Our findings are also consistent with those of Condron et al. (2012), who reported that despite higher annual pasture yields (i.e., 2.4- to 2.8-fold higher for the P fertiliser treatments compared with no P applied), the concentrations and amounts of organic C were similar across treatments. The absence of a significant accumulation of soil organic C in response to increased production was attributed to accelerated decomposition of organic matter inputs associated with a combination of improved pasture quality and increased earthworm activity (Condron et al. 2012).

Saggar et al. (1997) examined the partitioning and translocation of photosynthetically fixed C^{14} in a grazed hill pasture, and showed that while more of the C assimilated in a low fertility (LF) pasture was translocated below ground, a high fertility pasture (HF) still assimilated more total C and translocated more C below ground to roots. The increased C translocation below ground in a HF system did not translate into increased soil C stocks, and this points to systems where the total C pool is highly regulated. Greater earthworm biomass and diversity (Schon et al. 2019) and a shift from fungal to bacterial pathways in soil microbial and microfaunal processes (Parfitt et al. 2010) are present in the HF farmlet, suggesting a greater capacity for turnover of plant shoot and root biomass, and animal faeces. Based on the findings of our study and earlier findings by Lambert et al. (2000) and Schipper et al. (2011), the soil organic matter pool size remains relatively stable over time under permanent pasture under a diversity of pasture management regimes that would embrace the range of soil fertility and sheep stocking rates found in most hill country systems.

Sequestering of organic carbon C in soil offers an option for offsetting C atmospheric emissions. We examined soil C accumulation under a long-term P application and sheep-stocking regime grazing experiment. The hill country experiment has been running since 1975, with three distinct farmlets that received either no P fertiliser, an intermediate amount or an amount that exceeds annual maintenance. While farmlet regime had a minimal impact on soil C accumulation, slopes and aspects had a substantial impact and need to be considered in the design of soil sampling regimes that monitor soil organic carbon over space and time.

Acknowledgements

All the science, technical and farm and service staff that have been involved with the long-term study at the AgResearch Hill Country Research Station, Ballantrae since its establishment. The authors would like to recognise funding from the AgResearch Strategic Science Investment Fund.

References

Condron, L.M., Black, A., Wakelin, S.A., 2012. Effects of long-term fertiliser inputs on the quantities of organic carbon in a soil profile under irrigated grazed pasture. N. Z. J. Agric. Res. 55, 161-164.

Coonan, E.C., Richardson, A.E., Kirkby, C.A., Kirkegaard, J.A., Amidy, M.R., Simpson, R.J., Strong, C.L., 2019. Soil carbon sequestration to depth in response to long-term phosphorus fertilization of grazed pasture. Geoderma 338, 226-235.

Hewitt, A.E., 1998. New Zealand Soil Classification. Landcare Research Science Series 1, 2nd edition, Manaaki Whenua Press, Lincoln, New Zealand

Lambert, M.G., Clark, D.A., Mackay, A.D., Costall, D.A., 2000. Effects of fertiliser application on nutrient status and organic matter content of hill soils. N. Z. J. Agric. Res. 43, 127-138.

Lambert, M.G., Mackay, A.D., Ganesh, S., Upsdell, M.P., 2014. Responses of grazed New Zealand hill pastures to rates of superphosphate application. N. Z. J. Agric. Res., 1-16.

Mackay, A.D., Costall, D.A., 2016. Long-term changes in soil fertility in hill country. Hill Country – Grassland Research and Practice Series 16: 157-162.

Mackay, A.D., Vibart, R., McKenzie, C., Costall, D., Bilotto, F., Kelliher, F.M., 2021. Soil organic carbon stocks in hill country pastures under contrasting phosphorus fertiliser and sheep stocking regimes, and topographical features. Agricultural Systems 186, 102980.

McSherry, M.E., Ritchie, M.E., 2013. Effects of grazing on grassland soil carbon: a global review. Global Change Biol. 19, 1347-1357.

Saggar, S., Hedley, C., Mackay, A.D., 1997. Partitioning and translocation of photosynthetically fixed 14C in grazed hill pastures. Biol. Fertility Soils 25, 152-158.

Schipper, L.A., Dodd, M.B., Fisk, L.M., Power, I.L., Parenzee, J., Arnold, G., 2011. Trends in soil carbon and nutrients of hill-country pastures receiving different phosphorus fertilizer loadings for 20 years. Biogeochemistry 104, 35-48.

Schipper, L.A., Dodd, M.B., Pronger, J., Mudge, P.L., Upsdell, M., Moss, R.A., 2013. Decadal changes in soil carbon and nitrogen under a range of irrigation and phosphorus fertilizer treatments. Soil Sci. Soc. Am. J. 77, 246-256.

Young, R., Cowie, A., Harden, S., McLeod, R., 2016. Soil carbon and inferred net primary production in high- and low-intensity grazing systems on the New England Tableland, eastern Australia. Soil Research 54, 824-839.