Changes in soil carbon in hill-country under contrasting phosphorus fertiliser and sheep stocking rates

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Abstract
Carbon (C) measurements were analysed for soil sampled to two depths (0-75 and 75-150 mm) in 2003 and again in 2014 in three of the farmlets of a long-term phosphorus (P) fertiliser and sheep grazing experiment at the AgResearch Ballantrae Hill Country Research Station. The farmlets received either 125 kg/ha/year of single superphosphate (SSP) from 1975-1979 and none since (LFNF), or the same amount of SSP applied as for LFNF from 1975-1979 and 125 kg SSP/ha/year since 1980 (LFLF), or 625 kg/ha/year of SSP applied from 1975-1979, and 375 kg SSP/ha/year since 1980 (HFHF). Carbon concentration in soil at both sampling depths was not affected by differences in P fertiliser inputs and sheep stocking rate, but there were significant (P<0.001) slope x farmlet and aspect x farmlet interactions. Data from this long-term study provide science, policy and industry with invaluable insights into the changes in soil C stocks in pastoral hill-country soils.

Keywords: carbon stocks, fertiliser, sheep grazing, pasture production, long-term experiment

Introduction
Beef + Lamb NZ recently launched their Environment Strategy, which lays out a progressive long-term vision for the sector based on four priority areas - healthy productive soils, thriving biodiversity, clean water and reducing carbon (C) emissions (available at https://beeflambnz.com/environment-strategy). The Labour-led Government has announced its first steps towards making New Zealand C neutral by 2050 (available at https://www.newshub.co.nz/home/politics/2017/12/government-plans-to-go-carbon-neutral-by-2050.html). An interrelated question is: should soil C be included in the budget as the feasibility of a C neutral economy by 2050 is explored? Carbon stored in soil organic matter is an important reservoir within the global C cycle (Lal 2004). For example, a 5% increase in C stored in the 0-2 m soil layer could potentially reduce atmospheric CO_2-C by 16%. The ability to reduce atmospheric CO_2-C by this magnitude would offer an option for mitigating greenhouse gas emissions from farm systems, and would be of immediate interest to individual landowners, industry and government.

The challenge is understanding what practices could result in a sustained increase in the amount of C sequestered, and equally important, identifying the practices that place the current stocks of C at risk of depletion. The latter is also of interest to producers because of the pivotal role soil organic matter plays in the provision of a wide range of services (e.g. food, support, filtering, water regulation) from our pastoral soils (Dominati *et al*. 2010). Soil erosion from hill slopes represents the greatest risk to C stocks in hill-country (Lambert *et al*. 1984). This paper reports on changes in soil C between 2003 and 2014, from two soil depths (0-75 and 75-150 mm) on three slope positions and aspects, within three of the farmlets of the long-term P fertiliser and sheep-grazing experiment, located at the AgResearch Ballantrae Hill Country Research Station (Lambert *et al*. 2000).

Materials and methods
Study site
The Ballantrae Research Station is located in southern Hawkes Bay (408180S 1758500E), New Zealand, 300 m a.s.l. with an average air temperature of 12.8°C and an annual rainfall of 1270 mm. The soils are classified as Andosols and Luvisols with a silt-loam texture (Lambert *et al*. 2000).

Experimental farmlets
Three farmlets were sampled as part of the present study, including one which received an average 125 kg/ha/year of single superphosphate (SSP) from 1975-1979 and none since then (LFNF), one with the same amount of SSP applied from 1975-1979 as for LFNF and 125 kg SSP/ha/year applied subsequently (LFLF), and one which received an average 625 kg/ha/year of SSP applied from 1975-1979 and 375 kg SSP/ha/year applied subsequently (HFHF).

The farmlets have been continuously grazed predominantly with breeding ewes since 1975. Stocking rates had been 6.0 stock units (SU)/ha on all farmlets before 1975, where a stock unit is defined as a breeding-ewe-plus-single lamb equivalent consuming 550 kg dry matter (DM)/year. From 1976 until the present time, the stocking rate has increased to 10.6 SU/ha on the LFLF and has been as high as 16 SU/ha on the HFHF pasture. The stocking rate at LFNF has

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slowly dropped from 10.6 to about 6.0 SU/ha, the pre-experimental value before 1975 (Mackay & Lambert 2011).

Soil sampling and analysis

On each farmlet, soils were sampled to two depths (0-75 and 75-150 mm) in September 2003 and 2014. Within each farmlet, soil samples were taken from the 18 permanently marked sites established in 1975. The permanent sites cover three slope positions [low (1-12˚), medium (13-25˚), and high (>25˚)], and three aspects (centred on East, Southwest and Northwest). Two replicate sampling sites were used within each slope and aspect class combination within each farmlet. At each of the resultant 18 sites within each farmlet, 20 soil cores (2.5 cm diameter) were collected and bulked for analysis of soil C concentration. A single separate set of soil samples were taken using stainless steel rings (10 cm diameter) from each depth to determine bulk density at both sampling dates.

Soil samples were air-dried and passed through a 2 mm sieve. Each sample was mixed thoroughly and a subsample analysed for total carbon concentration (%) using a Leco CNS-2000 dry combustion analyser. This involved combustion at 1350^{o}C followed by detection of combustion gas (as CO_2) using infrared absorption measurement. For bulk density, the soil samples in the cores were dried at 105^{o}C for 36-48 h, and then weighed.

To quantify total C stocks/ha, soil C concentrations were multiplied by the bulk density measures from each site to obtain tonnes of C per hectare (t C/ha) and a weighted average for a farmlet was determined to account for the percentage of land in each of the slope and aspects classes. Across the three farmlets, the percentage of the land in low, medium and high slope positions ranged from 19-27%, 46-59% and 23-28%, respectively. The percentage of each farmlet facing SW was similar (17-29%), but there were differences in the percentage facing E (19-60%) and NW (26-50%).

Statistical analysis

A nested analysis of variance (nested ANOVA) was conducted to compare the effects of slope (Low, Medium and High) and aspect (Southwest, East and Northwest) for each year (2003 and 2014) within each farmlet (a unique combination of phosphorus fertiliser inputs and sheep stocking rate). Fishers Least Significant Differences post-hoc test was used to compare differences between means. The analyses were conducted using Genstat 18th edition (VSN International Limited). Means were considered significantly different at P<0.05 (with smaller values providing stronger evidence of significance) and P-values ≥0.05 but <0.10 were considered a trend.

Results

The concentrations of soil C within the 0-75 mm and 75-150 mm soil depths in both 2003 and 2014 were not influenced by differences in the P fertiliser history and sheep stocking rate treatments (farmlets). Because of the lack of farmlet replication data to explore the other two main effects (slope and aspect) independently (and hence the need of a nested ANOVA), the significance of slope and aspect as interaction effects were explored. There were significant (P<0.001) slope x farmlet (Figure 1) and aspect x farmlet (Figure 2) interactions. Within the 0-75 mm soil depth, C concentration in soil on the low slope (6.01 ± 1.28%) was 40% higher than on the high slope (4.28 ± 0.85%) in the majority of sites sampled across all three farmlets in both years (Figure 1). Similarly, within the 75-150 mm soil depth C concentration in soil on the low slope (4.32 ± 0.99%) was 29% higher than on the high slope (3.35 ± 0.64%) across the majority of sites in all three farmlets in both years (Figure 1). Carbon concentrations in soil on the medium slopes were similar to those of the low slopes in the LFLF farmlet, but distinctly different in the other two farmlets.

Carbon concentrations in soil on the SW (5.53±1.19%) and E (5.56±1.49%) aspects were 18% higher than on the NW (4.70±0.84%) aspect within the 0-75 mm soil depth in the majority of sites across farmlets in both years (Figure 2). Similarly, soil C concentrations on the SW (4.36±0.97%) and E (4.19±0.87%) aspects were 30% higher than on the NW (3.27±0.64%) aspect within the 75-150 mm soil depth across most sites in all three farmlets in both years (Figure 2). The exception was with the HFHF farmlet where differences in soil C concentrations between aspects were small.

Total C stocks/farmlet, when adjusted for slope and aspect classes and averaged for the two sampling dates, were 30.9 (±1.0), 30.9 (±1.4) and 33.7(±1.6) t/ha within the 0-75 mm soil depth in the LFNF, LFLF and HFHF farmlets, respectively. Corresponding values increased to 61.8 (±1.8), 60.0 (±1.0) and 62.6 (±1.4) t/ha when sampling was extended to 0-150 mm.

Discussion

It was not possible to separate the distinct effects of P fertiliser application and sheep stocking rate on soil C concentrations and stocks, given the farmlet experimental design. Notwithstanding this limitation, this long-term experiment provides, with the level of control over inputs and ongoing monitoring, a unique resource for examining changes in the biology, chemistry and physical properties of the soil, pastures and livestock under contrasting P fertiliser and sheep stocking management.

Estimates of annual pasture production obtained on the moderate slope in 2015-2016 were 6917, 9708

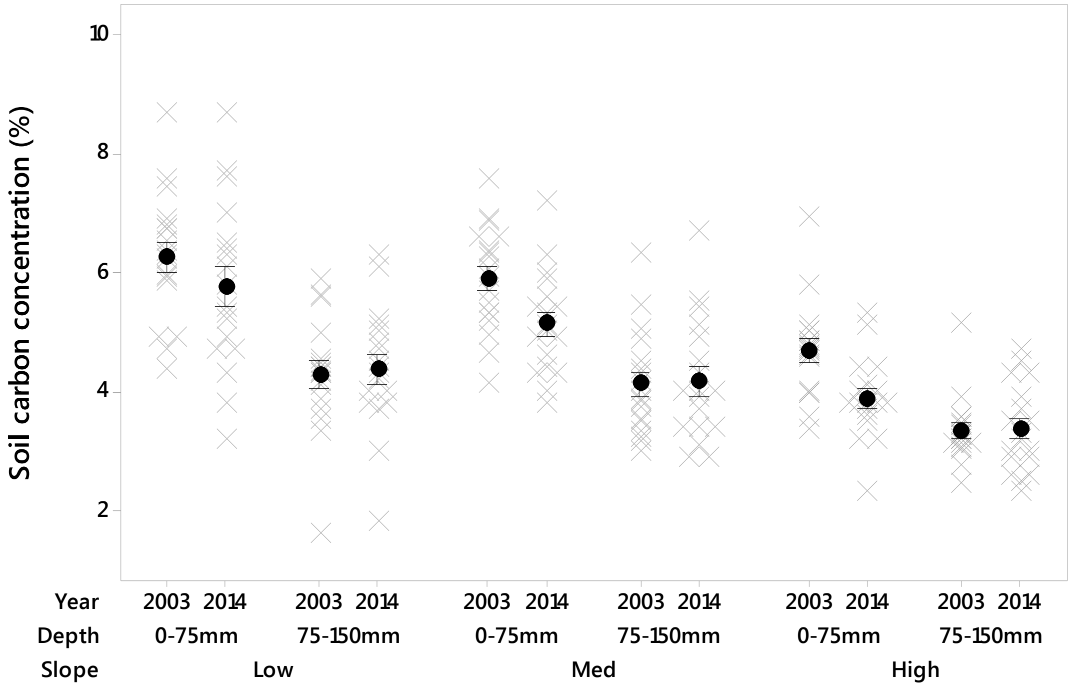

Figure 1 Mean soil carbon concentration (%) as influenced by slope (Low slope: 1-12˚, Medium slope: 13-25˚, High slope: >25˚) and soil depth (0-75 and 75-150 mm) across the LFNF, LFLF and HFHF farmlets in 2003 and 2014. Bars are one standard error from the mean.

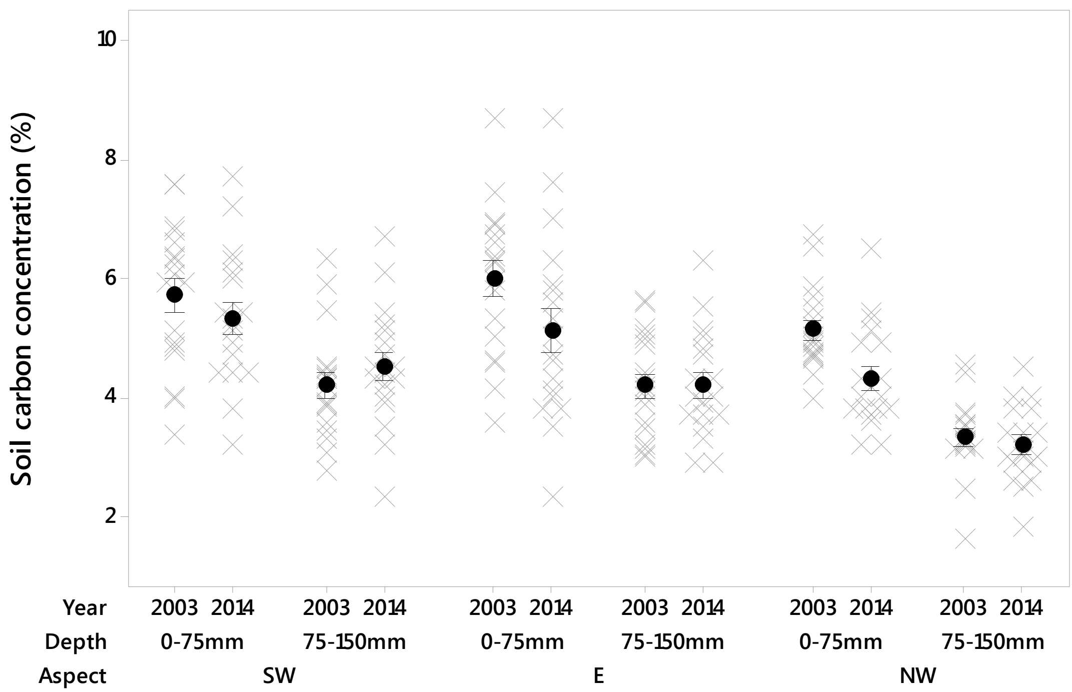

Figure 2 Mean soil carbon concentration (%) as influenced by aspect (SW Southwest, E East, NW Northwest) and soil depth (0-75 and 75-150 mm) across the LFNF, LFLF and HFHF farmlets in 2003 and 2014. Bars are one standard error from the mean.

and 11 289 kg DM/ha on the LFNF, LFLF and HFHF, respectively, which highlights the marked differences in primary production between the farmlets (Mackay *et al.* 2016). Currently, nominal sheep stocking rates are 50 and 120%, higher on the LFLF (10.6 SU/ha) and HFHF (16 SU/ha), than LFNF (6 SU/ha) farmlet. The LFNF farmlet is best described now as a low fertility (Olsen 6 μg/ml), extensive system (6 SU/ha), which would be unable to rear replacements to satisfactory liveweights under commercial farming practice. Notable parts of the medium and high slope areas of this farmlet are poorly grazed by the sheep. At the other end of the spectrum the HFHF system represents a high fertility soil (Olsen P >50 μg/ml), intensive livestock system (16 SU/ha). Under commercial practice annual fertiliser application rate would be reduced.

Despite these diverse biological systems, soil C concentrations within the 0-75 mm and 75-150 mm depths were not influenced by the contrasting P fertiliser inputs and sheep stocking rate of the three farmlets. Total C stocks when adjusted for slope and aspect in each farmlet, were 30.9, 30.9 and 33.7 t/ha in the 0 -7.5cm soil depth in the LFNF, LFLF and HFHF farmlets, respectively, averaged across the two sampling dates, increasing to 61.8, 60.0 and 62.6 t/ha, respectively, when sampling was extended to 0-150 mm. The absence of any differences in soil C stocks across the farmlets is consistent with previous findings at Ballantrae (Lambert *et al.* 2000), Whatawhata (Schipper *et al.* 2011), Winchmore (Condron *et al*. 2012) and Te Kuiti (Ghani *et al.* 2003). The simple explanation is that as primary production increases, associated losses also increase. Saggar *et al.* (1997) examined the partitioning and translocation of photosynthetically fixed ^{14}C in a grazed hill pasture at Ballantrae, and showed that while more of the C assimilated in the low fertility pasture was translocated below ground, a high fertility pasture assimilated more total C and translocated more C below ground to roots. The increased C translocation below ground in a high fertility system did not translate into increased soil C stocks, indicating higher turnover. A recent study by Schon *et al.* (2018) showed that earthworm abundance in the HFHF farmlet (428 ± 43/m^2) was nearly twice that of the LFNF farmlet (219 ± 36/m^2). This suggests that if more litter and dung is available to sustain a larger biological community, then that community ingests greater amounts of plant and root biomass, with little change in soil C stocks.

Lambert *et al*. (2000) reported an overall mean reduction in annual soil C stock (-1.7 ± 0.4 t C/ha) to a depth of 0-75 mm in the same long-term P fertiliser and sheep grazing study from 1972 to 1987. Linking the findings of the current study with those earlier measures of soil C from the farmlets, the trend for declining soil C from 1975 to 1987 is no longer apparent, despite the continuing divergence in the biological performance of the three farmlets. The findings of the current study are consistent with the findings from the Whatawhata P fertiliser and sheep grazing study (Schipper *et al.* 2011) from 1989 to 2006, but not from 1983 to 1989 when soil C stocks had increased. Current findings are also inconsistent with the findings of Schipper *et al.* (2014) who reported an average annual increase in soil C of 0.7 ± 0.3 t/ha on 23 commercial farms over 30 years, and those of Parfitt *et al.* (2014) who reported an average annual increase in soil C of 1.3 ± 1.0 t/ha on 19 commercial farms over 6 years. The factors contributing to the C sequestration rates reported by Schipper *et al.* (2014) and Parfitt *et al.* (2014) remain unclear. Like the sites in the long-term study at Ballantrae, the sites sampled by both Schipper *et al.* (2014) and Parfitt *et al*. (2014) were from stable locations, limiting the influence of recent erosion processes on C sequestration rates.

In contrast to management treatments, both slope (Figure 1) and aspect (Figure 2) had a pronounced influence on soil C concentrations and by default on C stocks across the farmlets. The differences in soil C with slope are likely to be the product of several factors, including differences in soil development and a wide range of biological processes from plant growth through to microbial activity, as they are influenced by the distinct soil moisture and temperature regimes found across different slope and aspect classes (Lambert & Roberts 1978). The grazing animal transferring a disproportionate amount of the dung from medium and high slope to low slope positions (Saggar *et al.* 1990) potentially amplifies these differences. An understanding of the attributes of the landscape and the possible influence on livestock behaviours become important factors, when assessing the total soil C stocks in these landscapes.

The long-term P fertiliser and sheep grazing experiment at AgResearch Ballantrae Hill Country Research Station is an invaluable resource for exploring the long-term changes in hill pastoral systems. Data from the long-term experiment will contribute to the national inventory on soil C stocks in hill-country. New knowledge of the influence of slope position, aspect, phosphorus fertiliser inputs and grazing sheep on soil C inputs, losses and stocks will assist in refining the current protocols for sampling soil C stocks in hill-country. The project provides science, policy and industry with further insights into the changes in soil C stocks in hill-country.

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