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Trends in soil carbon and nutrients of hill-country pastures receiving different phosphorus fertilizer loadings for 20 years

L. A. Schipper · M. B. Dodd · L. M. Fisk ·
I. L. Power · J. Parenzee · G. Arnold

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Abstract There are few records of long-term trends in soil C and N in grazed pasture systems but recent measurements have demonstrated unexplained losses on New Zealand lowlands. To determine whether losses were also occurring in hill country pastures, we analyzed archived soil samples collected between 1983 and 2006 from two slope classes (steep and easy) at the Whatawhata Research Centre. Soils were Ultic Hapludand and Typic Haplohumult on the easy slopes (10–20°), and Typic Haplohumult on the steeper slopes (30–40°). Soil samples (0–75 mm) had been collected from paddocks that were fertilized with six different loading rates of P (ranging from 0 to 100 kg P ha^{-1} -$year^{-1}$ since 1985). This range of P loadings allowed us to determine whether P inputs would regulate trends in soil C and N. While there were significant temporal trends in C and N ($P < 0.05$), these were not unidirectional and trends were not dependent on P loading rate. On average, soil C initially increased during the first 6 years of the trial at 0.270% C $year^{-1}$ (1.56 t ha^{-1} $year^{-1}$) and 0.156% C $year^{-1}$ (1.06 t ha^{-1} $year^{-1}$) on easy and steep slopes, respectively. Subsequently, there was no significant trend in soil C on the easy slopes but soil C declined at −0.066% $year^{-1}$ (0.45 t ha^{-1} $year^{-1}$) on the steep slopes. Similarly, soil N increased between 1983 and 1989 at 0.025% N $year^{-1}$ (144 kg ha^{-1} $year^{-1}$) and 0.012% N $year^{-1}$ (82 kg ha^{-1} $year^{-1}$) on easy and steep slopes, respectively. Post-1989, small but significant losses of total N were measured on the steep slopes of 0.004% $year^{-1}$ (27 kg N ha^{-1} $year^{-1}$) ($P < 0.05$) with no trend on the easy slopes. Two potential causal factors for these decadal-scale patterns were identified, operating via changes in primary productivity. These were lower S inputs from 1989 due to a change in fertilizer type, and a series of relatively dry summers during the 1990s. These significant inter-annual trends in soil C and N complicate attempts to measure long-term changes in soil organic matter associated with land use change and management practices. This study has demonstrated the potential error associated with infrequent soil sampling to determine long-term trends in soil C and N; large gains or losses could have been detected at Whatawhata depending on when sampling started and finished. Understanding these long-term trends in soil organic matter dynamics and driving factors requires more long-term sampling trials.

L. A. Schipper (✉) · L. M. Fisk · J. Parenzee
Department of Earth and Ocean Sciences, University of Waikato, Private Bag 3105, Hamilton 3240, New Zealand
e-mail: schipper@waikato.ac.nz

M. B. Dodd
AgResearch, Private Bag 11008, Palmerston North 4442, New Zealand

I. L. Power
AgResearch, Private Bag 3123, Hamilton, New Zealand

G. Arnold
Landcare Research, Private Bag 11052, Palmerston North 4442, New Zealand

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Abbreviation
SU Stocking units

Introduction

Intensive and extensive pastoral grazing for food production occurs in many regions of the world (Steinfeld et al. 2006). As with many other land uses, productivity from this land use has increased with improved plant and animal genetics and health, increased stocking rates, and increased inputs such as fertilizer, irrigation, and feed. There are a wide range of environmental impacts as a result of this intensification, including reduced biodiversity, increased emission of greenhouse gases, water depletion, erosion and water pollution from surplus nutrients and biological contamination (Steinfeld et al. 2006).

In New Zealand, conversion of indigenous forest vegetation to grazing land started about 160 years ago (Parliamentary Commissioner for the Environment 2004; MacLeod and Moller 2006). As fertilizer technology, aerial topdressing, soil science and genetics improved after World War I, a period of intensification occurred, with phosphate fertilizers and lime being used to raise soil nutrient availability and stimulate clover growth and N fixation. In more recent times (1980s onwards), increasing use of N fertilizer on flat land has occurred as land use has become more intensive with a desire for higher productivity (Parliamentary Commissioner for the Environment 2004). Consequently, soil fertility (N and P), compaction, and pH of pastures are now greater than in the same soils under indigenous vegetation (Sparling and Schipper 2004).

To make progress towards more sustainable land use, it is important to understand the changes that occur in soil properties during initial development of land from indigenous vegetation and the subsequent changes that occur as land use intensifies. Understanding trends in the amounts of soil organic matter is particularly important because organic matter plays a central role in maintaining many soil functions, such as soil structure, storage of nutrients, cation exchange capacity and as the food source for soil biota. Furthermore, soil organic matter is a large store of global C and relatively small changes in total C in the world's soils could have large effects on CO_2 concentrations in the atmosphere (Lal 2003).

There have been a range of reports addressing whether long-term pastures are a sink or a source of CO_2 (e.g., Allard et al. 2007; Aires et al. 2008; Bellamy et al. 2005; Chou et al. 2008). A recent study of New Zealand pasture soils on flat land revealed large losses of soil C of about 1 t C ha^{-1} $year^{-1}$ and losses of N of about 90 kg C ha^{-1} $year^{-1}$ over the two decades before 2005 (Schipper et al. 2007). These findings were in contrast to earlier work by Tate et al. (1997) who found no change in soil C between the 1950s and 1992. The reasons for differences between the findings of Tate et al. (1997) and Schipper et al. (2007) are not fully understood, but in more recent times (1990s onwards), pasture has been grazed more intensely with increased stocking rates supported by imported feed and increased N fertilization (MacLeod and Moller 2006).

The decline in soil N reported by Schipper et al. (2007) was also unanticipated as N is generally expected to increase in pasture soils following development and subsequent intensification such as increased fertilizer inputs (Jackman 1964, Schipper et al. 2004). Generally, N accumulates in soil organic matter during the development of pasture as net immobilization of fertilizer N and N fixation exceeds N mineralization. Consequently, the C:N ratio of pasture soils declines with time and C:N ratios are generally lower in pastoral soils than in forestry soils (Sparling and Schipper 2002, 2004). In the long term, there will be an upper limit to the amount of N that can accumulate in soils, assuming that soil C does not change. However, there is little information on the rate at which soil organic matter accumulates N and how long accumulation will continue (Schipper et al. 2004).

The majority of this previous New Zealand work (Tate et al. 1997; Schipper et al. 2007) was focused on pastures on flat to rolling land (<15° slope), which comprises about 55% of the pastoral land area in New Zealand (Manderson and Palmer 2006). Whether such widespread losses in C and N also occur in hill country pastoral soils is not known and needs to be determined to define the extent of soil C change at a national scale. While management of pastures on hill country in New Zealand has been less intensive than that on flat land, in terms of lower stocking rates and inputs of fertilizer P and N, there are indications of increasing intensification, achieved in part by higher N fertilizer use (Parliamentary Commissioner for the Environment 2004). It is unclear what the effect of this intensification might have on soil C and N stocks. There would be considerable concern if increased fertility of pasture on hill country led to significant losses of both C and N as has been observed on flat land. In one of the few studies of hill country, Lambert et al. (2000) measured declines in soil C of about 200 kg C ha^{-1} $year^{-1}$ in pastures receiving both high and low fertilizer inputs between 1972 and 1987 while soil N was maintained in the low input, and increased (by 19 kg ha^{-1} $year^{-1}$) in the high input treatment.

To better understand decadal soil C and N dynamics in hill country pastures, we analyzed soil samples that had been collected and archived over a 26-year period from a phosphorus fertiliser trial based at the Whatawhata Research Centre. This site provided an opportunity to measure changes in soil C and N in hill country that had been in pasture for at least 40 years before the start of the trial. During this trial, P fertilizer had been applied to duplicate paddocks at six different rates ranging from 0 to 100 kg P ha^{-1} $year^{-1}$. Our objective was to determine whether soil C and N had changed over the period of the trial and whether any change was dependent on rates of P fertilizer addition.

Materials and methods

Site description and management

This study was based at the Whatawhata Hill Country Research Centre (37.48° S, 175.05° E), 22 km west of Hamilton, North Island, New Zealand on undulating to very steep low-altitude hill country (45–370 m above sea level). The climate at the Research Centre is mild to warm and humid, with a mean annual rainfall of approximately 1,630 mm and mean annual temperature of 13°C. A phosphate fertilizer trial was established at the site in 1980 on a 14.2 ha area subdivided into 20 paddocks of 0.25–1.22 ha in size, with easy (10–20°) to steep (30–40°) slopes and a north-westerly aspect. The soils were a soil association of the Dunmore series [Typic Impeded Allophanic Soils (Hewitt 1998); Ultic Hapludand (Soil Survey Staff 2006)] and Naike series [Typic Orthic Granular Soils (Hewitt 1998)]; Typic Haplohumult (Soil Survey Staff 2006) on the easy slopes, and Kaawa series [Typic Yellow Ultic Soils (Hewitt 1998); Typic Haplohumult (Soil Survey Staff 2006)] on the steeper slopes. Soil pH was 5.3 on the easy slopes and 5.2 on the steep slopes.

Fertiliser application

The trial site was converted to pasture from indigenous scrub and forest in the 1920s (Table 1). The pasture was fertilized with single superphosphate (NPKS = 0-9–0-11) at an average rate of 36 kg P ha^{-1} $year^{-1}$ for at least 12 years before the start of the trial. The fertiliser trial started in 1980 when five single superphosphate application rates were established: 10, 20, 30, 50, and 100 kg P ha^{-1} $year^{-1}$ on four replicate paddocks. Fertiliser was applied in late summer/early autumn. After 1989, single superphosphate was replaced with triple superphosphate (NPKS = 0-21–0-1). From 1985 to 2006, the P rate treatments continued on only two of the replicate paddocks, which were included in this study. Fertiliser

Table 1 History of pasture development and fertilizer inputs at the experimental site on the Whatawhata Research Centre

Year	Management
c. 1920	Site cleared from indigenous forest
1944	Earliest aerial photo showing developed pasture at the site
1968–1980	Superphosphate inputs of 36 kg P ha^{-1} $year^{-1}$
1980–1984	Five loading rates of P fertilizer onto four replicate paddocks. Rates: 10, 20, 30, 50, 100 kg P ha^{-1} $year^{-1}$
1984–2006	Five loading rates of P fertilizer above continued on two replicate paddocks for each rate. Fertilizer withheld on other two replicate paddocks—two of these paddocks (with initial loading of 10 kg P ha^{-1} $year^{-1}$) selected as nominal controls 0 kg P ha^{-1} $year^{-1}$ for the current study

application ceased on the other two replicate paddocks and we also included the two paddocks that had received 10 kg P ha^{-1} $year^{-1}$ between 1980 and 1985 as nominal unfertilised controls (0 kg P ha^{-1} $year^{-1}$) for the current study.

Grazing management

Between 1984 and 1988, paddocks were rotationally grazed by Romney-cross wethers or ewes from December to lambing (August) and set stocked through lambing to weaning (November). Pre-conditioning paddocks were used to minimize the transfer of nutrient via excreta from high P input to low P input paddocks. Stocking rates were adjusted to maintain pasture utilization across the P loading rates, from $\sim$12 SU ha^{-1} (SU = stock units) on the unfertilized paddocks up to $\sim$18 SU ha^{-1} on the highest fertilizer rate paddocks. From 1989 to 1991 the paddocks were continuously grazed with ewe hoggets at a similar SU range and from 1991 onwards the grazing management reverted to that for the 1984–1988 period.

Soil sampling

Throughout the trial, soil samples were collected from all paddocks in February or March of each year. The sampling methodology changed during the course of the trial. Between 1983 and 1988, ten soil cores (0–70 mm) were taken along each of five transects on both easy (10–20°) and steep (30–40°) slope classes, from each paddock (20 replicate cores per paddock and slope class). At the time of sampling, the cores were sectioned into 0–30 mm and 30–70 mm depth fractions and were bulked by depth for each transect. For samples collected between 1993 and 2006, 15–20 replicate soil cores (0–75 mm) were taken from both easy and steep sites randomly distributed across each paddock, and samples were bulked by slope class. All soils were air-dried, passed through a 2-mm sieve, stored in plastic containers and archived. For the years when samples were collected by transect (1983–1988) we bulked subsamples from the five transects to give a single sample for each depth from each paddock/year and slope combination before C and N analysis (see below). Both sampling approaches sampled across the same areas of each slope class within each paddock.

Intact soil samples for bulk density determination were collected at the end of the trial. Three replicate stainless steel rings (100 mm diameter, 75 mm high) were cut and pressed into the soil of each paddock/slope combination. These soil samples were dried to constant weight at 105°C and dry bulk density calculated.

Soil analysis

Prior to C and N analysis, any large visible fragments of roots and grass were removed from air-dried soil and the sample then ground in a ball mill before total C and N analysis using a LECO furnace (TruSpec, St Joseph, Mississippi). Data were corrected for moisture factors which were obtained for each air-dried soil sample following drying to a constant weight at 105°C. C:N ratio was calculated on a mass basis. Olsen P was determined using the MAF Quicktest method of Cornforth and Sinclair (1984).

Climate data and modeling

Daily weather data have been collected at the Whatawhata Research Centre since 1972 as part of the National Climate Database now administered by NIWA. We accessed daily rainfall, minimum air temperature, maximum air temperature, 5 cm soil temperature, relative humidity, vapour pressure, solar radiation, and windspeed data for the site using the AgResearch interface for the Virtual Climate Station (VCS) data. The derivation of the VCS data is described by Tait and Woods (2007). With this data we ran a 32-year pasture growth simulation (1972–2004) using ECOMOD (Johnson et al. 2008) to produce estimates of pasture transpiration as a proxy for net primary production (Moir et al. 2000). The simulation was run once as a cutting trial, with 8 harvests per year, assuming P inputs of 30 kg P ha^{-1} $year^{-1}$ on a ryegrass/white clover sward. The soil profile was initialized using mean values for soil C and N measured in this study and physical/hydrological properties based on soil texture data collected at the site (29% sand, 49% silt, 22% clay—K. Mueller, pers. comm.).

Data analysis

Between 1983 and 1988, soil samples were collected from 0 to 30 mm and 30 to 70 mm, and while these were analyzed separately for total C and N, for data analysis we calculated a depth-weighted mean to obtain a %C or %N for 0–70 mm. In more recent times (1993 onwards), samples were collected to 75 mm. We assumed that the % C and N in samples from the top 70 mm and top 75 mm would be the same as these topsoils are well mixed.

Analysis of trends over time used a linear mixed effect model as implemented in the nlme package of R (Pinheiro et al. 2008). Maximum likelihood was used to estimate effects, and hypothesis tests were based on changes in likelihood using approximate *F*-ratios. Separate components of variance were included for paddocks and slopes within paddocks, and the variance of pre-1990 measurements, when transect sampling was used, was estimated separately from post-1990 measurements. The 'broken stick' model, that is separate lines pre- and post-1989, had higher likelihood than polynomial or exponential curves and so for consistency was used throughout.

Where reported, differences were significant at $P < 0.05$ unless stated otherwise.

Results

Changes in Olsen P

Olsen P increased during the trial in paddocks receiving P fertilizer inputs of 20 kg P ha^{-1} $year^{-1}$ or greater (Table 2). Olsen P values for paddocks with loading rates of less than 30 kg P ha^{-1} $year^{-1}$ remained below values needed for optimum pasture growth (Morton and Roberts 1999). While Olsen P was greater on the easy slopes than steep slopes the rate of increase in Olsen P over time was similar for both steep and easy slopes (Fig. 1).

Table 2 Soil Olsen P (μg g^{-1}) of soil collected from the easy and steep slopes of paddocks (two replicates) receiving different rates of P fertilizer

Year/slope	Phosphorus fertilizer loading rate (kg P ha^{-1} $year^{-1}$)											
	0 (control)		10		20		30		50		100	
1983 easy	ND	7	7	ND	ND	6	9	ND	16	ND	ND	21
1985 easy	10	10	11	10	11	10	10	11	25	30	37	35
1986 easy	11	8	9	11	9	12	13	16	27	28	36	41
1987 easy	7	7	11	8	14	8	11	11	33	29	41	51
1988 easy	9	8	10	8	13	9	14	11	41	28	44	55
1993 easy	12	12	11	10	24	11	16	15	55	48	62	56
1996 easy	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
2004 easy	10	10	10	13	24	14	36	30	112	128	124	200
2005 easy	10	7	11	16	17	50	41	15	86	75	116	197
2006 easy	9	10	13	13	43	14	47	49	84	62	107	143
1983 steep	ND	5	7	ND	10	6	10	ND	12	17	ND	24
1985 steep	12	7	9	9	10	9	10	10	19	30	35	43
1986 steep	11	6	6	9	11	10	11	13	24	36	43	50
1987 steep	8	5	7	6	13	6	10	9	26	35	ND	57
1988 steep	9	6	7	8	11	7	10	10	10	38	52	68
1993 steep	9	7	7	10	13	7	14	15	73	29	58	99
1996 steep	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
2004 steep	5	5	6	6	12	7	19	14	71	ND	98	146
2005 steep	5	5	6	7	18	21	25	7	72	59	112	149
2006 steep	7	6	11	10	18	9	30	22	90	69	136	152

ND not determined

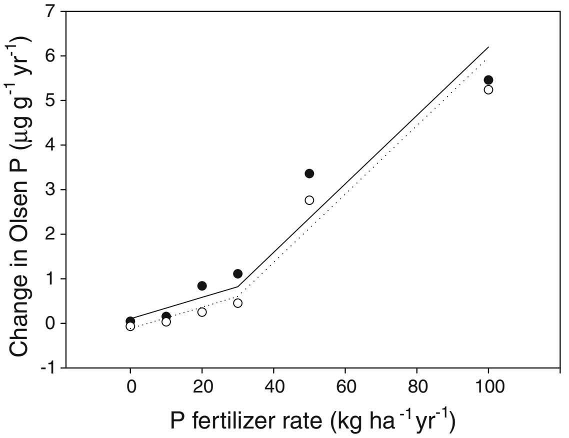

Fig. 1 Mean annual rate of change in Olsen P as a function of P fertilizer application rate. *Open circles* are from steep slopes and *closed circles* from easy slopes. *Solid line* and *dotted line* is the fitted broken stick model to easy slope and steep slope data, respectively

Bulk density

Bulk densities were significantly greater ($P = 0.001$) on the steep slopes (mean 0.91 t m^{-3}, standard deviation 0.06 t m^{-3}) than the easy slopes (mean 0.77 t m^{-3}, standard deviation 0.09 t m^{-3}). This is not unexpected because of differences in soil types on easy and steep slopes, particularly soils on easy slopes were allophanic and these soils generally have lower bulk densities than other mineral soils. However, differences in P fertilizer application rate (and consequent differences in sheep stocking rate) had no measurable influence on soil bulk density, on either steep or easy slopes.

Changes in soil carbon and nitrogen

While there were very clear and predictable increases in soil Olsen P content on the treatments with higher P application rate, trends in total % C and N were not unidirectional (Tables 3, 4, 5). Soil C increased significantly between 1983 and 1989 at 0.270 and 0.156% C $year^{-1}$ on easy and steep slopes, respectively. However, between 1989 and 2006, soil C did not change significantly on the easy slopes and declined significantly on the steep slopes (−0.066% C $year^{-1}$). Changes in total soil N followed changes in total C (Table 5). Initially, % N increased significantly at the beginning of the trial at 0.025 and 0.012% N $year^{-1}$ on easy and steep slopes, respectively. After 1989, there were relatively small but significant losses of total N on the steep slopes of 0.004% $year^{-1}$ and no significant change on the easy slopes. There was no evidence that changes in %C and %N were dependent on P fertilizer loading.

As there were no differences in bulk density across treatments we used the average bulk density derived for easy slopes (0.77 t m^{-3}) and steep slopes (0.91 t m^{-3}) to convert % total C or % total N to mass per unit area. Thus, the initial increases in soil C were calculated as 1.56 t C ha^{-1} $year^{-1}$ for easy slopes and 1.06 t C ha^{-1} $year^{-1}$ for the steep slopes in the top 75 mm for the first 6 years of the trial. Subsequently, the decline in soil C for the steep slopes was calculated as 0.45 t C ha^{-1} $year^{-1}$ for the last 17 years of the trial with no significant change in total C on the easy slopes. For the first 6 years of the trial, total N increased at 144 kg N ha^{-1} $year^{-1}$ for easy slopes and 82 kg N ha^{-1} $year^{-1}$ for steep slopes. After 1989, there were no significant changes in total N on the easy slopes but on the steep slopes, total N decreased at 27 kg N ha^{-1} $year^{-1}$.

C:N ratio did not change between 1983 and 1989, but subsequently C:N ratio declined significantly on both slope classes, as %C declined faster than %N.

Climate data and modeled plant transpiration

Rainfall data for the Whatawhata Research Centre indicated quite different patterns between the 1980–1989 and 1990–1999 periods (Fig. 2a). Mean rainfall during the summer months (December, January, and February) of the 1990s was lower than the long term average by up to 25 mm each month. In contrast, the mean rainfall for these months in the 1980s was similar (December, February) or greater than (January) the long term average. Over the April–September period, the 1990s appeared to have more rainfall and the 1980s appeared to have less rainfall, compared with the long-term monthly averages.

Soil temperature data also indicated differences between the 1980s and 1990s (Fig. 2b). During the autumn–winter period (April–August) the 5 cm mean monthly soil temperatures were 0.3–0.9°C warmer in the 1990s compared to the previous decade. In addition, the mean soil temperature in February was over 1°C warmer during the 1990s. However, mean monthly

Table 3 Soil C (%) of soils collected from easy and steep slopes of paddocks receiving different rates of P fertilizer (two replicate paddocks)

Year/slope	Phosphorus fertilizer loading rate (kg P ha^{-1} $year^{-1}$)											
	0 (control)		10		20		30		50		100	
1983 easy	ND	7.8	8.1	ND	ND	6.5	6.8	ND	7.3	ND	ND	8.6
1985 easy	6.5	8.5	8.7	9.4	8.5	6.6	7.0	8.0	8.0	9.8	7.4	10.2
1986 easy	7.5	8.6	8.9	9.9	8.7	7.3	7.6	7.8	8.1	10.3	7.2	9.7
1987 easy	7.1	9.4	9.4	9.7	9.4	7.1	7.6	7.9	8.5	10.8	7.4	9.9
1988 easy	7.7	8.9	10.0	10.1	9.7	7.5	8.2	8.9	9.2	10.4	7.7	10.0
1993 easy	8.0	8.7	10.7	9.8	10.6	7.5	10.2	7.8	9.2	8.4	8.0	10.4
1996 easy	6.2	8.0	8.9	10.1	9.0	7.9	9.7	7.1	8.7	10.0	9.0	10.6
2004 easy	9.1	9.5	9.5	8.1	8.7	7.0	7.9	8.4	8.6	9.0	7.1	11.5
2005 easy	6.8	9.3	9.6	9.4	8.4	8.1	8.9	6.6	7.9	10.3	7.0	10.7
2006 easy	8.4	9.5	10.0	9.9	10.2	8.1	7.9	8.0	9.1	11.1	7.1	10.4
1983 steep	ND	6.8	6.3	ND	5.9	5.8	5.8	ND	6.7	6.1	ND	6.9
1985 steep	6.2	7.0	6.5	6.5	6.3	6.2	6.5	5.8	7.0	6.4	6.2	8.3
1986 steep	6.2	7.2	6.6	6.8	6.4	7.0	6.9	7.0	7.2	6.6	6.4	8.7
1987 steep	6.2	7.3	6.9	6.6	6.7	6.1	6.5	6.2	7.7	6.6	ND	8.3
1988 steep	6.7	7.4	6.9	7.2	6.7	6.6	6.7	6.5	7.6	6.9	6.5	8.4
1993 steep	6.2	7.8	6.6	8.1	7.4	6.0	6.1	5.8	8.0	5.6	6.0	8.3
1996 steep	4.6	5.9	7.2	8.0	7.3	6.5	7.8	6.3	6.8	6.8	6.8	8.2
2004 steep	6.1	7.1	6.2	5.8	6.0	6.1	6.1	5.5	6.0	ND	5.3	5.4
2005 steep	5.5	5.8	5.7	5.4	5.9	5.2	4.6	5.4	5.2	5.8	5.5	6.2
2006 steep	6.0	6.5	6.8	7.1	6.2	6.1	6.6	5.5	7.3	6.6	6.0	7.7

ND not determined

spring soil temperatures (September–November) were 0.2–0.7°C cooler in the 1990s compared to the 1980s.

These differences in rainfall and temperature resulted in considerable variation in modeled pasture transpiration over the 32-year modeled period (Fig. 3). Estimated annual pasture transpiration averaged 518 mm between 1972 and 2004. For the 1980s, 8 out of 10 years had transpiration rates above this long-term mean; whereas, for the 1990s, 9 out of 10 years were below the mean with a substantial relative deficit in the early 1990s.The results also indicated a return to above-average annual transpiration from 2000 onwards.

Discussion

Changes in total carbon and nitrogen

Our primary objective was to determine whether hill country pastures were losing C and N as observed in pastures on flat land (Schipper et al. 2007) and in the one other published hill country study (Lambert et al. 2000). However, in the current study there was no unidirectional trend in soil C and N over time; rather we measured increases for the first 6 years followed by either no change or declines in C and N over the subsequent 17 years. This implicates an important shift in the input-output balance occurring around 1989 that led to decadal-scale pattern of soil C and N dynamics. Broadly, there are two potential drivers for this shift—changes in climate (temperature and moisture) and management (fertilizer inputs and stock policies) which are discussed in detail further below.

A secondary objective was to determine whether a range of P fertilizer inputs to these soils would alter the balance between C and N inputs and outputs, resulting in different rates of change in soil C and N. In New Zealand, the productivity of legume-based hill country pastures at an annual time scale is generally dependent on an adequate P supply (Lambert 1987; Ledgard et al.

Table 4 Soil N (%) of soil collected from easy and steep slopes of paddocks receiving different rates of P fertilizer (two replicate paddocks)

Year/slope	Phosphorus fertilizer loading rate (kg P ha^{-1} $year^{-1}$)											
	0 (control)		10		20		30		50		100	
1983 easy	ND	0.67	0.69	ND	ND	0.59	0.60	ND	0.62	ND	ND	0.70
1985 easy	0.54	0.71	0.72	0.77	0.69	0.59	0.59	0.69	0.67	0.87	0.65	0.83
1986 easy	0.65	0.70	0.75	0.80	0.71	0.64	0.66	0.69	0.67	0.91	0.62	0.80
1987 easy	0.64	0.81	0.83	0.82	0.83	0.65	0.70	0.71	0.74	0.96	0.68	0.84
1988 easy	0.67	0.75	0.85	0.86	0.80	0.66	0.73	0.77	0.79	0.92	0.66	0.84
1993 easy	0.71	0.73	0.91	0.82	0.92	0.66	0.89	0.70	0.76	0.73	0.71	0.87
1996 easy	0.56	0.71	0.78	0.85	0.78	0.69	0.82	0.63	0.74	0.89	0.78	0.92
2004 easy	0.81	0.86	0.87	0.73	0.78	0.67	0.73	0.75	0.76	0.83	0.65	1.06
2005 easy	0.66	0.85	0.89	0.88	0.77	0.78	0.85	0.63	0.72	0.99	0.67	1.03
2006 easy	0.76	0.85	0.91	0.90	0.94	0.74	0.76	0.74	0.78	1.06	0.67	0.89
1983 steep	ND	0.56	0.52	ND	0.50	0.49	0.49	ND	0.56	0.52	ND	0.55
1985 steep	0.54	0.58	0.52	0.54	0.53	0.54	0.54	0.51	0.55	0.56	0.53	0.68
1986 steep	0.54	0.56	0.54	0.55	0.55	0.60	0.56	0.60	0.58	0.54	0.55	0.70
1987 steep	0.55	0.60	0.58	0.55	0.60	0.53	0.54	0.54	0.63	0.55	ND	0.67
1988 steep	0.58	0.59	0.56	0.58	0.58	0.56	0.55	0.56	0.62	0.56	0.56	0.67
1993 steep	0.55	0.65	0.54	0.64	0.66	0.54	0.53	0.49	0.65	0.47	0.54	0.70
1996 steep	0.42	0.48	0.61	0.67	0.63	0.57	0.68	0.53	0.56	0.58	0.61	0.66
2004 steep	0.53	0.62	0.50	0.48	0.53	0.51	0.53	0.47	0.50	ND	0.48	0.45
2005 steep	0.48	0.48	0.51	0.47	0.52	0.47	0.43	0.47	0.46	0.52	0.50	0.53
2006 steep	0.53	0.53	0.55	0.60	0.53	0.53	0.56	0.48	0.64	0.59	0.54	0.66

ND not determined

Table 5 Modeled % total C or N, the rate of change in total C and N, and the C:N ratio from 1983 to 1989 and from 1989 to 2006 at Whatawhata Research Centre farm for both steep and easy slopes

Estimates	Total C		Total N		C:N ratio	
	Easy	Steep	Easy	Steep	Easy	Steep
Value at 1983 (%)	7.6	6.2	0.65	0.52	11.7	12.0
Rate of change (% $year^{-1}$)	**0.270** (0.030)	**0.156** (0.029)	**0.025** (0.003)	**0.012** (0.003)	0.003 (0.026)	−0.002 (0.025)
Value at 1989 (%)	9.3	7.2	0.80	0.60	11.7	11.9
Rate of change (% $year^{-1}$)	−0.024 (0.012)	**−0.066** (0.012)	0.000 (0.001)	**−0.004** (0.001)	**−0.045** (0.007)	**−0.019** (0.007)
Value at 2006 (%)	8.7	6.0	0.81	0.52	10.8	11.5

Standard errors of rates of change are given in brackets. Numbers in bold were significant at 5% level

1987), and previous studies of initial pasture development with P fertilizer input have shown accumulation of soil C (Jackman 1964, Williams and Haynes 1990). The Olsen P values for the different paddocks ranged from less than 10 to more than 100 μg g^{-1} spanning the optimum Olsen P values (20–30 μg g^{-1}) for pasture production in hill country (Morton and Roberts 1999). Despite this wide range of Olsen P across the paddocks, we found no supporting evidence that P fertilizer loading altered the changes in either C or N in the surface soils of this site.

While annual pasture dry matter production at this site has been shown to increase with increasing P fertilizer loading rate (up to 28% on easy slopes and 6% on steep slopes: Gillingham et al. 1990; Rowarth and Gillingham 1990), this effect was not translated

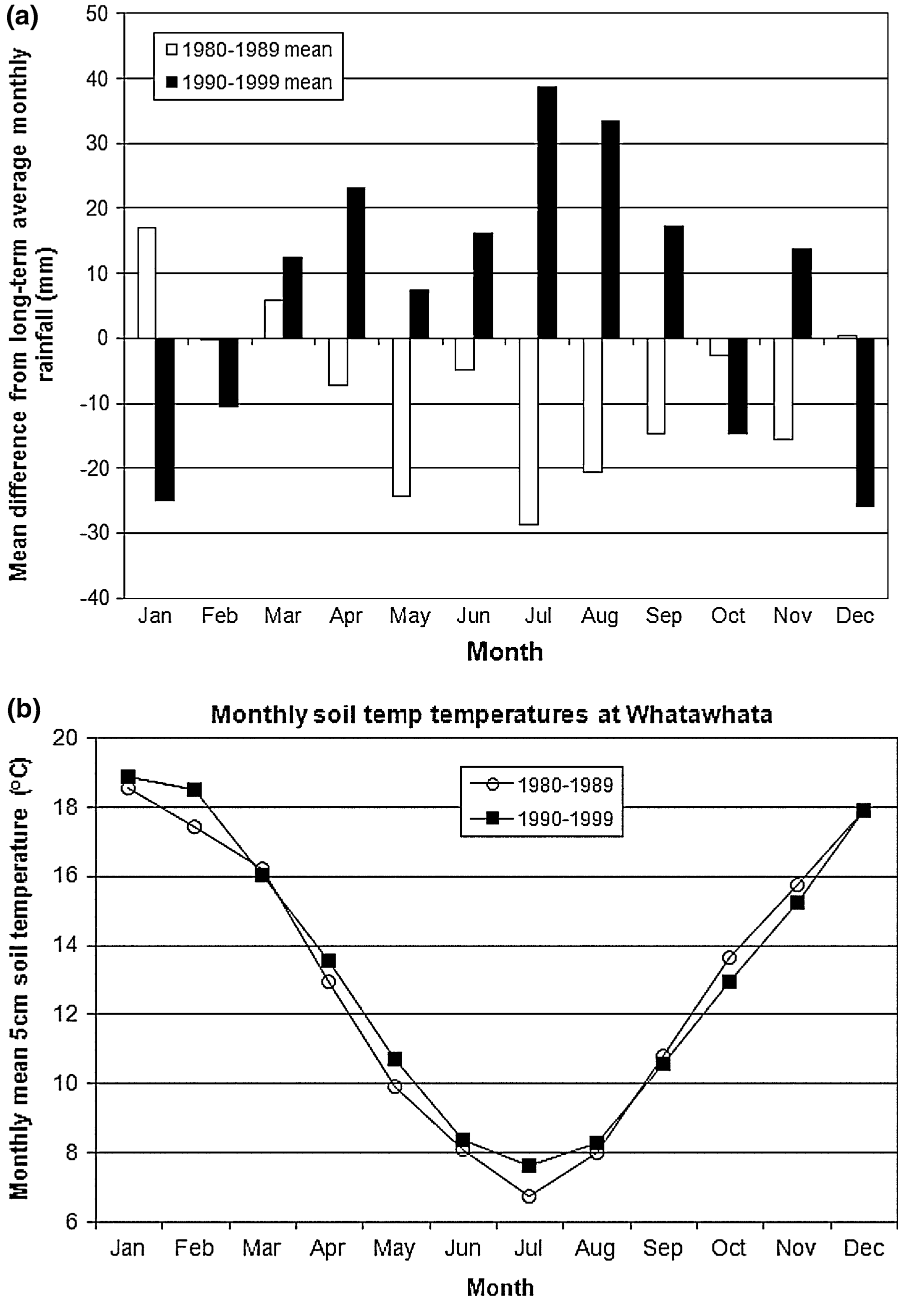

Fig. 2 **a** Difference from the long-term average rainfall (mm) at Whatawhata in each month, averaged for the 1980s and 1990s. **b** Mean monthly 5 cm soil temperature (°C) at Whatawhata, averaged for the 1980s and 1990s

into increased soil C and N. Greater net primary production due to higher P inputs might be expected to result in higher C and N inputs to soil via litter turnover, as well as via greater dung and urine inputs resulting from the greater stocking rates on the higher P input treatments (Lambert et al. 2000). However, it appears that the greater losses also associated with higher stocking rates have compensated this effect, i.e., C losses such as animal respiration (CO_2) and eructation (CH_4) and higher N losses via leaching (Cuttle et al. 1998).

The lack of a P fertility effect on trends in soil C and N was in contrast to findings by Lambert et al. (2000) who measured temporal trends in C and N

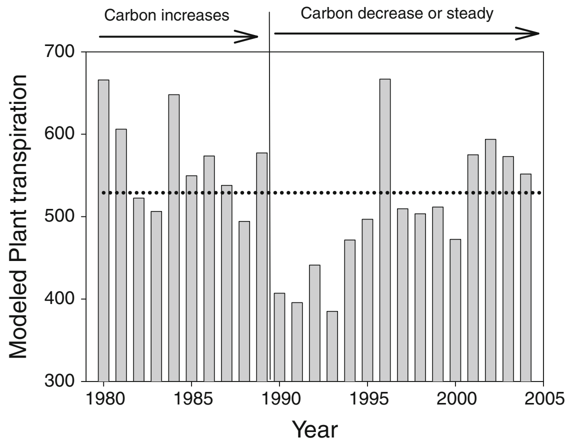

Fig. 3 Modeled plant transpiration during the trial based on climate data using ECOMOD (Johnson et al. 2008) *dotted line* represents the average transpiration during the trial

over 15 years at high fertility pasture sites (that received >36 kg P ha^{-1} $year^{-1}$) and low fertility pasture sites (that received 12 kg P ha^{-1} $year^{-1}$). They measured declines of about 200 kg C ha^{-1} $year^{-1}$ in both high and low fertility pastures while soil N increased (19 kg N ha^{-1} $year^{-1}$) in high fertility sites only. They attributed the increase in soil N at the higher fertility site to increased clover growth and N fixation stimulated by P fertilizer. Consequently, we expected that soil N would also increase more in the Whatawhata paddocks with greater P fertilizer inputs. This was not the case, but it is pertinent to note that there was no significant increase in legume abundance at Whatawhata in response to increased P inputs during the 1980s (Gillingham et al. 1990) or in 1998 (Dodd and Ledgard 1999). We may not have observed a difference in the accumulation of soil N across the fertility gradient because clover production and N fixation at this site were not limited by soil P status but by soil moisture status, as seen in similar environments (Gillingham et al. 2003).

That the temporal changes in C and N were consistent across fertiliser loadings implied that the cause(s) of these changes were due to variables other than those which associated with P loading. At this site, a number of variables are considered below. They include: (a) long-term changes in bulk density; (b) changes in management practice (in particular fertilizer type and stocking policy); and, (c) changes in the climate regime.

Bulk density samples were only collected at the end of the sampling period and we have assumed that there were no systematic changes in bulk density during the trial. We feel this assumption is justified because the pasture had been grazed mainly by sheep rather than cattle since the 1940s and under this management we suggest that bulk density would have stabilised by the beginning of the trial. Additionally, we did not observe increases in bulk density in paddocks with greater P fertilizer loading which supported greater sheep stocking rates. A lack of change in bulk density with time is in agreement with a number of other studies of long-term pastures where there were no significant changes in bulk densities over several decades (Jackman 1964, Lambert et al. 2000, Schipper et al. 2007).

It is possible that a sulfur or micronutrient deficiency could have developed during the latter years of the fertilizer trial due to the switch from single superphosphate to triple superphosphate in 1991. This would have had the effect of decreasing fertilizer-based S inputs to the site by tenfold for each treatment, based on the sulfur content of these fertilizers (11 vs. 1%, respectively). It is worth noting that because of its proximity to the west coast, the site probably receives about 7 kg S ha^{-1} $year^{-1}$ in atmospheric deposition (Edmeades et al. 2005). Thus, for the highest and lowest fertilizer input rates, total S inputs will have been reduced to 7 and 17 kg S ha^{-1} $year^{-1}$, respectively. The latter figure is still at the low end of fertility maintenance recommendations for the site and stocking rate (Morton and Roberts 1999). However, the range is such that, as noted above, if variation in nutrient inputs were driving the long-term trends in soil C and N, we would have expected to observe a fertilizer rate treatment effect particularly post-1989. This argument applies equally to S or micro-nutrients as it does to P inputs. Limited soil test data from 1991 onwards showed that while soil sulfate-S levels (MAF Quicktest, Cornforth and Sinclair 1984) were suboptimal, they were in fact indicating a pattern of increase from a site mean of 5 μg g^{-1} in 1991 to 8 μg g^{-1} in 1999 (Power unpubl. data).

The climate data for the Whatawhata site showed evidence of decadal scale differences in the seasonal patterns of temperature and rainfall (Fig. 2a, b), which appeared to be broadly associated with the decadal scale patterns in soil C and N dynamics. That is, relatively drier summers and warmer winters during the 1990s when soil C and N was declining, compared to the 1980s when soil C and N was increasing, with a change point around 1989. Unfortunately, due to the lack of sufficient annual sampling during the 1990s it was not possible to perform a robust correlation between soil C changes and antecedent climate. Thus, the association remains tentative, but a mechanistic basis can be hypothesized. In response to the climatic patterns, ECOMOD simulated lower annual total plant transpiration during the 1990s compared with the 1980s (Fig. 3). Transpiration is strongly correlated to cumulative pasture production (Moir et al. 2000); suggesting that annual pasture production was relatively lower in the 1990s compared to the 1980s.

The effect of summer droughts on total soil C is not straightforward, as inputs from photosynthesis and losses through soil respiration (microbial and root) will both decline as water becomes limiting (Baldocchi 2008). However, microbial activity can be sustained at very low soil moisture content when plant growth will cease. Microbes continue to respond rapidly to relatively small increases in moisture content following rain (Baldocchi 2008). Decreased C inputs through lower photosynthesis coupled with continuing microbial respiration during drier periods could then contribute to declines in soil C from 1990 onwards. Carbon losses associated with drought can be quite rapid and relatively large; in Oklahoma, Myers (2001) measured a net loss of -1.55 t C ha^{-1} in just 90 days from grassland soils during a drought. Similarly, Aires et al. (2008) measured net C losses of -0.49 t C ha^{-1} year^{-1} during a drought whereas there was net gain of soil C (1.9 t C ha^{-1} year^{-1}) a year of normal rainfall in a Mediterranean grassland. We suggest that a plausible explanation for the trends in soil C at Whatawhata was a series of summer droughts in the 1990s that decreased plant production and consequently C inputs to the soil. Microbial decomposition of litter inputs and soil organic matter was not decreased to the same extent and the net effect was a decline in soil C.

Differences in the rate of change in soil N can also be linked to evidence of lower pasture productivity post-1990. In an adjacent 10-year white clover persistence experiment at Whatawhata, Dodd et al. (2001) measured a large decline in clover abundance from about 30–50% to less than 5% between 1991 and 1999, which they attributed to the dry summers observed in the 1990s. Decreases in N fixation as a result of lower pasture clover content would lead to smaller N inputs to soils and the rate of N accumulation would also slow. Clover growth and N fixation is strongly dependent on adequate soil moisture, particularly for the summer-active white clover (Ledgard et al. 1987). Changes in soil N are frequently correlated to changes in soil C in grassland systems (Conant et al. 2005) predominantly because N is covalently bonded to C in organic matter so that net mineralization of C makes N more susceptible to loss via processes such as leaching, denitrification and volatilization.

C:N ratio

The C:N ratio declined post-1990 dropping from 11.7 to 10.8 on easy slopes and from 12 to 11.5 on steep slopes. The decline in C:N ratio was in agreement with the general observation that pasture soils have a lower C:N ratio than the forested systems from which they were developed (Sparling and Schipper 2004). It is unclear how much further this ratio will continue to decline. We have previously proposed that there is a minimum C:N ratio of 10 that can be attained in pasture systems below which net immobilization of N no longer occurs as the storage capacity of the organic matter is saturated (Schipper et al. 2004). This lower value of 10 was based on the general observation that globally most soils do not have topsoil C:N ratio of less than 10 (Batjes 1996). Based on current trends, the C:N ratio of these soils will reach 10 in about 20 years on the easy slopes and 100 years on the steep slopes, but this assumes that soil C remains constant. As with the changes in C and N, there was no effect of P fertilizer loading rate on the rate of change in C:N ratio, in contrast to the study of Lambert et al. (2000) who measured initially greater declines in C:N ratio at sites with greater P loading.

Slope class effects

Differences in rates of change and stocks of C, N and Olsen P between the slope classes were expected (Saggar et al. 1999; Lambert et al. 2000; Ledgard 2001). Saggar et al. (1999) demonstrated that in hill country there was greater photosynthesis on easy slopes than steep slopes; for example, transfer of C to soil on easy slopes was 930 kg ha^{-1} year^{-1}; whereas, on steep slopes transfer of C to the soil was 555 kg ha^{-1} year^{-1}. Similarly, Ledgard (2001) summarized N fixation on different slope classes and showed that N fixation on easy slopes was about 55 kg N ha^{-1} year^{-1}, but on steep slopes it was considerably lower at about 15 kg ha^{-1} year^{-1}. Additionally, animals graze both easy and steep slopes but excreta is mainly deposited on easy slopes, transferring C, N and P from steep slopes to easy slopes (Williams and Haynes 1990). These lower inputs to steep slopes would lead to lower total stocks of C, N and P, and lower rates of change in comparison to the equivalent easy slopes. There may also have been transfer of topsoil C, N and P via erosion from steep slopes and deposition on easy slopes, representing a greater net loss pathway on steep slopes.

Implications for measuring changes in C and N

A limitation of some of the previous studies that examined long-term changes in soil C and N in pastures systems was that there were only two sampling dates for each site (Tate et al. 1997; Schipper et al. 2007). Consequently there is little information on inter-annual variability of soil C and N. To obtain information on inter-annual variations requires experimental sites where soil samples are collected through time; however, regularly-sampled long-term sites are uncommon. We are aware of only two other NZ grassland locations where soil samples have been collected annually for greater than 10 years—Winchmore (Nguyen and Goh 1990; Metherell 2003) and Ballantrae (Lambert et al. 2000). Studies such as these were often originally established with other objectives in mind, such as testing alternative management practices to maximize above-ground pasture production (e.g., Gillingham et al. 1990) and hence the supplementary data record is not sufficiently complete to examine new hypotheses such as effects on soil C. There can also be changes in sampling protocols and in management of the sites as different experiments are conducted in the context of the site as a "field laboratory", as occurred at Whatawhata. These changes have unforeseen consequences in terms of our ability to interpret the mechanisms driving the observed patterns in the response variable of interest. The patterns we have observed at the Whatawhata site, while not necessarily representative of the hill country drystock sector as a whole (due to the site specific fertilizer input and climatic regime) do present a challenge to our conventional view of soil C and N being stable under long-term developed pastures.

To make predictions about long-term trends in soil C and N associated with changing management practices such as increased fertilizer application, information is needed on the inter-annual variability of soil C and N stocks driven by climate. The challenge is to measure long-term trends in C and N associated with land use change or intensification of management practices against inter-annual oscillations in C and N driven by external drivers, such as changes in short-term and long-term climate. Our study highlighted the importance of multiple sampling times when studying trends in C and N. If soil samples had been taken only during the 10 year period of the 1980s we would have concluded that hill country pastures were gaining between 1.06 and 1.56 t ha^{-1} year^{-1} depending on slope class examined. Conversely, if samples had been taken only from the 1990s onwards, we would have concluded that changes in total C ranged from steady state (no change) to losses of 0.45 t ha^{-1} year^{-1}, again depending on slope class. Multi-year trends in soil C and N in response to variations in climate may limit our ability to detect relatively small but important longer-term trends in total stocks associated with land use or management. The significance of these multi-year trends can only be adequately addressed through maintaining long-term trials.

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