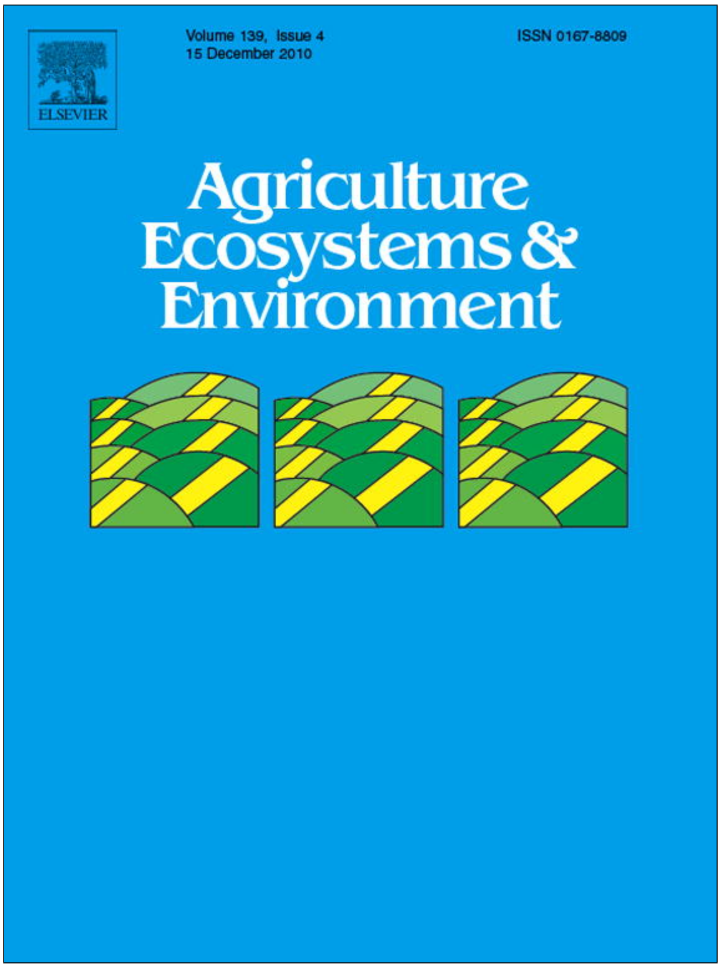
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Gains and losses in C and N stocks of New Zealand pasture soils depend on land use

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ABSTRACT

Previous re-sampling of 31 New Zealand pasture soil profiles to 1 m depth found large and significant losses of C and N over 2–3 decades. These profiles were predominantly on intensively grazed flat land. We have extended re-sampling to 83 profiles, to investigate whether changes in soil C and N stocks were related to land use. Over an average of 27 years, soils (0–30 cm) in flat dairy pastures lost 0.73 ± 0.16 Mg C ha^{-1} y^{-1} and 57 ± 16 kg N ha^{-1} y^{-1} but we observed no significant change in soil C or N in flat pasture grazed by "dry stock" (e.g., sheep, beef), or in grazed tussock grasslands. Grazed hill country soils (0–30 cm) gained 0.52 ± 0.18 Mg C ha^{-1} y^{-1} and 66 ± 18 kg N ha^{-1} y^{-1}. The losses of C and N were strongly correlated, and C:N declined significantly. Further, results reported to 60 and 90 cm show that the pattern of losses and gains extend beyond the IPCC accounting depth of 30 cm. Specific causes for the soil C and N changes are unknown, but appear to be related to land use. In general, the losses under dairying correspond to systems with greater stocking rates, fertiliser inputs and removal of C and N in exported products. Gains in hill country pastures may be due to long-term recovery from erosion and disturbance following land clearance. The unexpected and contrary changes of C and N in different pasture systems (initially thought to be at steady state) demonstrates the need for global and national-scale collection of robust data investigating soil biogeochemical changes, not only for grasslands but also for other land uses. Re-sampling of soils can constrain the directions and magnitude of soil C and N change associated with land use and management to underpin C and N inventories and correctly identify mitigation options.

1. Introduction

Gains or losses of C from soil organic matter due to changes in land use and management are of critical importance to the global C budget because of the large amounts of C held in soil in comparison to the atmosphere (Smith, 2008). Soil profile C accumulation or depletion is predominantly dependent on the balance of inputs (e.g., photosynthesis, organic matter imports, re-deposition of eroded C) and losses (e.g., ecosystem respiration, product exports, leaching, and erosion), and management practices and climate variations that alter these inputs and outputs can result in large changes in stocks of soil profile C. The impacts of land use or management have focussed on changes in soil C following conversion of grassland or forest to cropland (Guo and Gifford, 2002), forest to grassland or cropland (Murty et al., 2002), afforestation of grassland (Laganière et al., 2010), management of cropland (Senthilkumar et al., 2009) and pasture management practices (Conant et al., 2001, 2007).

Grazed grasslands systems occupy 26% of global ice-free land and are undergoing large changes in management, primarily aimed at increasing production (Steinfeld et al., 2006). Studies of grazed land at regional scales have measured gains, losses and no change in C and N (e.g., Conant et al., 2001; Bellamy et al., 2005; Smith et al., 2007; Sleutel et al., 2007; Hopkins et al., 2009; Meersmans et al., 2009; Zhang et al., 2010). However, these studies are unlikely to be representative of pastures under year-round grazing such as found in New Zealand grasslands. There are 11.1 million ha of grazed land in New Zealand with 5.4 million ha on flat to gently rolling land (<15°) and 5.7 million ha of hill country (>15°). The majority of this grazed land is dominated by introduced pasture grasses, with a smaller area vegetated by native tussock grassland adapted to low soil fertility. Tussock grasslands can be modified through burning and addition of phosphorus fertiliser. Dairy farming is primarily based on flat to gently rolling land (1.5 m ha occupied by lactating cows) with high producing pasture species. The remaining grazed land is used for a variety of other more extensive farming prac-

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tices such as: raising sheep, beef cattle, deer or non-lactating dairy cows, which can be collectively termed "drystock farming". In general, pasture under dairy farming is more intensively managed than drystock farming with dairy farmers applying greater amounts of fertilisers to support higher stocking rates, rotational grazing and more recently with increased imports of feed stocks (MacLeod and Moller, 2006; Clark et al., 2007; Parfitt et al., 2006, 2008; Mackay, 2008).

There have been two large scale studies of changes in soil C and N in New Zealand pastures. Tate et al. (1997) found no change in topsoil C of pasture soils between 1950 and 1992, but this study only sampled to 15 cm and was unable to correct for bulk density. The majority of these sites were sampled prior to the increased intensification of pasture management in New Zealand including increased use of N fertilisers and increased animal stocking rates that occurred in the 1990s. A more recent study, re-sampled 31 pasture sites (to a meter depth and with measured bulk density) around New Zealand and measured large losses of both C (1.06 Mg C ha^{-1} y^{-1}) and N (91 kg N ha^{-1} y^{-1}) over 17–30 years (Schipper et al., 2007). This latter study focussed predominantly on intensive dairying sites on flat land.

While there has been considerable focus on changes in soil profile C associated with understanding the global C cycle and maintenance of soil quality, changes in soil N are also important. In general, conversion of indigenous vegetation to pasture is followed by net immobilisation of N into organic matter, with a decline in soil C:N ratio (Jackman, 1964; Schipper and Sparling, 2010). This net immobilisation acts as a sink for excess N, with rates of N accumulation decreasing with time following conversion. The extent and rate of net N immobilisation in pasture systems are poorly understood (Schipper et al., 2004; Watson et al., 2007; Schipper and Sparling, 2010) but can continue for a century (Johnston et al., 2009). Once this immobilisation sink is enriched with N, there are presumably greater amounts of labile N available for plant uptake but also subject to loss pathways including denitrification, volatilisation, and leaching.

Our objective was to extend our initial re-sampling of soils (Schipper et al., 2007), which had predominantly focussed on dairy pastures on flat land, to determine whether changes in soil C and N also occurred in other important pastoral land uses in New Zealand including drystock farming on flat land, drystock farming on hill country and tussock grassland, also extending the geographic spread of information.

2. Methods

2.1. Site selection

Sample sites were selected from the National Soils Database (NSD) based on a number of criteria that minimised errors of re-sampling sites. 83 sites were resampled between 2002 and 2010, and the same methods were used as previously described in Schipper et al. (2007). The NSD is a point database containing locations, horizon descriptions, and data of some 1500+ profiles that were initially sampled between 1960 and 1992 from around New Zealand. Not all profiles in the NSD were originally sampled in the same way and we selected a subset of profiles that had been sampled for bulk density, and had soil samples air-dried, archived and were available for re-analysis for total C and N. We only included sites that were in pasture when first sampled and eliminated profiles with stones, peaty or buried top-soils.

For this subset of sites, the location information in the NSD was supplemented with notes on original site information, site diagrams and photos to re-locate sites. In some cases, the pedologists who originally took samples were also able to help with site relocation. Sites that had obviously been disturbed were not sampled. We believe that we were typically able to resample within ∼10 m radius of the original sampling site. We compared contemporary land use with notes in the NSD to ensure that landuse was similar, and where possible we contacted landowners to verify this.

Prior to sampling, we augered the soil to assess that the soil horizons were similar to those from the earlier sampling, then a pit was dug to expose the soil profile. The profile was sampled by the same depths as originally described; generally this was by horizon, although for some profiles, thick horizons were split into two depths. To collect a soil sample for chemical analysis, a slice of the whole horizon (or each half of upper thick horizon when this had been split) was taken. This sample was returned to the laboratory, sieved through 5 mm to remove coarse roots, air-dried, sieved through 2 mm, and analysed for total C and N using a Leco FP2000 analyser (TruSpec, St. Joseph, Mississippi). At the same time, archived soils samples were retrieved and analysed in the same run on the Leco furnace to minimise analytical errors.

Two bulk density samples (1 above the other) were taken from the either side of the centre of each horizon by carving around a brass ring (68.8 cm^3 volume) using a sharp knife to minimise disturbance of soil structure. Soil samples were dried at 105 °C to a constant weight, weighed and bulk density calculated. In the original sampling for the NSD, most bulk density samples were taken using a 200-core sampler (Soil Moisture Equipment Corp., Santa Barbara, California), which uses a small slide hammer to hammer a corer with two rings separated by a 1 cm spacer into the soil. In a side-by-side comparison, we showed that the slide hammer approach underestimated bulk density in comparison to carving each individual ring into the soil by about 5% possibility due to soil shattering by the slide hammer (Schipper et al., 2007; Parfitt et al., 2010a). After correcting for the different methods for collecting bulk density we found no significant change in bulk density between samplings, which is in agreement with a number of temporal studies of pasture soils (Jackman, 1964; Lambert et al., 2000). Consequently, we have used the bulk densities from contemporary carving to calculate volumetric C and N stocks.

2.2. Data analysis

Stocks of soil C and N were calculated as the product of the C or N concentration, bulk density of the horizon, and horizon depth. Soil profiles were sampled to different depths depending on the original sampling. For ease of comparison, we calculated stocks to 30 cm increments (full data is available from authors). However, samples were collected by horizon rather than by depth and to estimate stock to 30 cm, we summed stocks of C and N of horizons above 30 cm depth, and added in a linear proportion of the total C or N in the next horizon depending on depth remaining to 30 cm. The same approach was used to calculate stock of C and N to 60 and 90 cm. Because not all profiles were sampled to 60 cm and 90 cm there were fewer profiles for these depths. We excluded one previously-reported profile in the Schipper et al. (2007) study – the Rawerawe (SB9633) profile (dairy pasture on flat land), which was an outlier with very large C and N losses in peaty material.

The depths of the upper soil layer ranged from 0–7 cm to 0–26 cm with the average being 0–13 cm. Change in soil C and N for the 0–10 cm layer was estimated using the data for 0–10 cm where it was measured. Where the surface horizon was thicker than 10 cm, the changes were estimated by arithmetic scaling back to 10 cm.

We divided soil profile data into 4 groups: (i) dairy grazing on flat land, (ii) drystock grazing on flat land, (iii) drystock grazing on hill country (>15°) in the North Island, and (iv) drystock grazing on tussock grasslands in the South Island. These separations were based on the differences in the way that stock is managed on

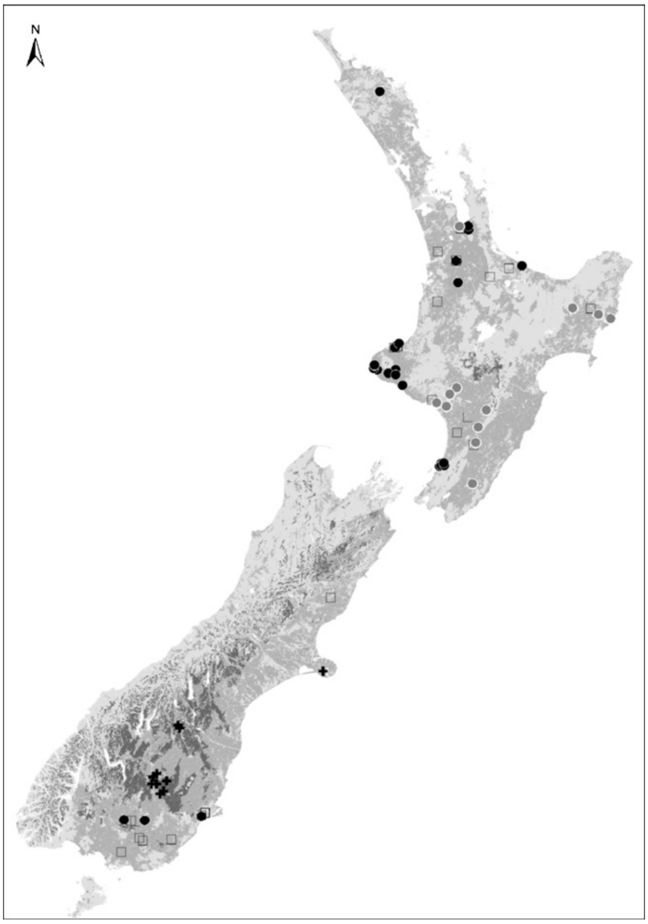

Fig. 1. Sites resampled throughout New Zealand. Pasture land is medium grey, tussock grassland dark grey and non-pasture land is light grey. (●) Dairy pasture on flat land, (●) drystock on hill country, (+) drystock on tussock grass land, and (□) drystock on flat land.

these land units. For each group we calculated average changes in soil C and N (for 0–0.3 m, 0–0.6 m, and 0–0.9 m) along with standard errors to determine if changes were significant different from 0, i.e., no change in profile C or N. The significance of changes in C:N ratio between samplings was tested against the null hypothesis that $C{:}N_{initial}/C{:}N_{final} - 1$ was zero, using both a *t*-test and non-parametric Wilcoxon signed rank test in JMP 9.0.2 (SAS Institute). Reported *P*-values are consistent with both tests. Locally weighted regression of the depth trends was completed using the loess function in *R* (version 2.9.1), identically to the results reported in Schipper et al. (2007). Unless stated otherwise all reported differences were significant at 5% level.

3. Results

3.1. C and N change

We re-sampled 83 profiles under pasture in New Zealand for C and N (Fig. 1), and some soils gained C and N while others lost C and N during the 13–40 years between sampling (Fig. 2, supplementary material). The dairy soils on flat land lost 0.73 Mg C ha^{-1} y^{-1} for the top 30 cm of soils and 1.21 Mg C ha^{-1} y^{-1} for the top 90 cm (Table 1). There was no significant change in soil C in flat land and tussock grasslands grazed by drystock, but significant gains in C were measured for soils under pasture on North Island hill country (0.52 Mg C ha^{-1} y^{-1} for the top 30 cm; 1.00 Mg C ha^{-1} y^{-1} for the top 90 cm). Changes in soil N were strongly correlated to changes in soil C (adjusted $R^2 = 0.79$, $n = 83$, $P < 0.001$), with soils under dairying on average losing 112 kg N ha^{-1} y^{-1}, and hill country soils on average gaining 118 kg N ha^{-1} y^{-1} for the top 90 cm (Fig. 2 and Table 2).

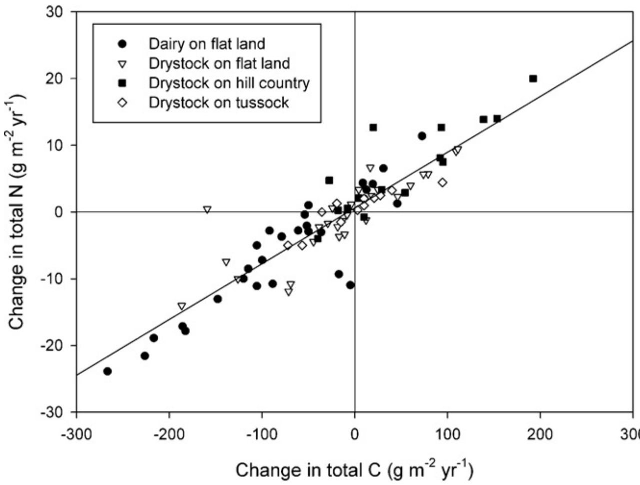

Fig. 2. Rate of change in total C and total N for 30 cm profile depths for the four categories of land use (fitted line has an adjusted $R^2 = 0.79$, $n = 83$, $P < 0.001$).

Changes in soil C extended throughout the profile (Table 1 and Fig. 3). The loss of C under dairying was 0.73 Mg C ha^{-1} y^{-1} for 0–30 cm soil layer, greater than that estimated for the 0–10 cm layer (0.27 Mg C ha^{-1} y^{-1}). The changes in soil C at 30 cm depth (ΔC_{0-30}) were linearly correlated to changes in top 60 cm (ΔC_{0-60}): $\Delta C_{0-60} = 1.23 \pm 0.07\ \Delta C_{0-30} - 0.19 \pm 0.14$ (mean ± standard error, adjusted $R^2 = 0.81$, $n = 76$, $P < 0.001$). Change in soil C of top 30 cm was less well correlated with changes in top 90 cm (ΔC_{0-90}) with the equation of: $\Delta C_{0-90} = 1.23 \pm 0.14\ \Delta C_{0-30} - 0.33 \pm 0.28$ (mean ± standard error, adjusted $R^2 = 0.56$, $n = 65$, $P < 0.001$).

The C:N ratios of the sites, calculated to 30 cm, generally decreased between samplings (Fig. 4) with $P < 0.002$. Decreases in

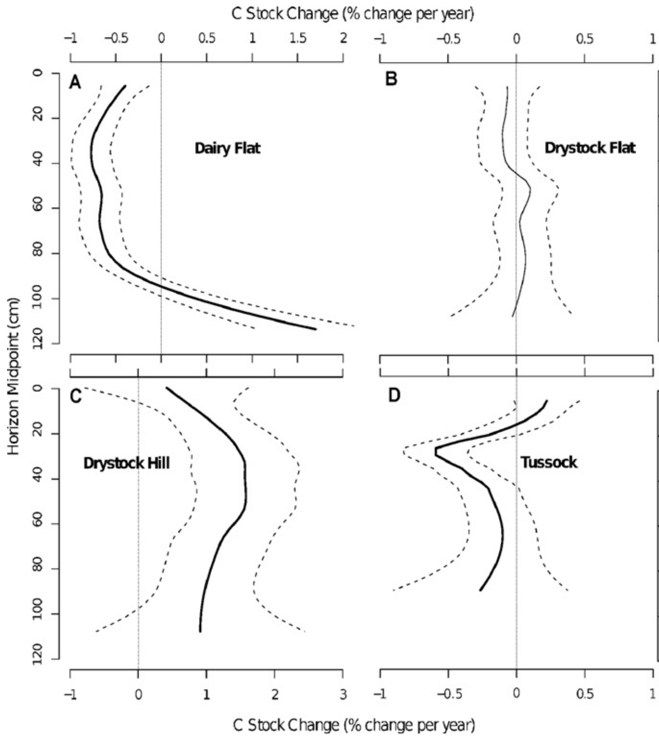

Fig. 3. Percentage annual change in soil C through the profile for different land use groupings. Dashed lines are ±one standard error.

Table 1
Change in total C of grazed land for different land categories Mg C ha^{-1} y^{-1} for 10, 30, 60 and 90 cm depth. SEM in parenthesis.

Land form	Land use	0–10		0–30		0–60		0–90	
		n	Average	*n*	Average	*n*	Average	*n*	Average
Flat	Drystock	27	−0.07 (0.08)	27	−0.14 (0.15)	27	−0.31 (0.20)	22	−0.31(0.27)
Flat	Dairy	29	−0.27 (0.10)**	29	−0.73 (0.16)***	27	−0.99 (0.20)***	25	−1.21 (0.25)***
North Island hill	Drystock	15	0.21 (0.09)*	15	0.52 (0.18)*	15	0.70 (0.28)*	12	1.00 (0.37)*
South Island tussock	Drystock	12	0.07 (0.10)	12	0.00 (0.13)	10	−0.08 (0.19)	3	−0.35 (0.08)*

SEM, standard error of the mean. Data for 0–10 cm are estimated from data for the surface layers which had an average depth of 13 cm.
* Significantly different from 0 at $P < 0.05$.
** Significantly different from 0 at $P < 0.01$.
*** Significantly different from 0 at $P < 0.005$.

Table 2
Change in total N of grazed land for different land categories kg N ha^{-1} y^{-1} for 10, 30, 60 and 90 cm depth.

Land form	Land use	0–10		0–30		0–60		0–90	
		n	Average	*n*	Average	*n*	Average	*n*	Average
Flat	Drystock	27	−4(7)	27	−8(12)	27	−20(16)	22	−19(21)
Flat	Dairy	29	−19(9)*	29	−57(16)***	27	−85(20)***	25	−112(23)***
North Island hill	Drystock	15	31(10)**	15	66(18)**	15	83(28)*	12	118(40)*
South Island tussock	Drystock	12	9(5)	12	4(9)	10	−6(9)	3	−9(23)

SEM, standard error of the mean. Data for 0–10 cm are estimated from data for the surface layers which had an average depth of 13 cm.
* Significantly different from 0 at $P < 0.05$.
** Significantly different from 0 at $P < 0.01$.
*** Significantly different from 0 at $P < 0.005$.

C:N ratio were larger for higher C:N ratios, with C:N ratios above the median value (11.7) of C:N$_{initial}$ decreasing by 4 ± 1% of the intial value ($P < 0.005$). The decrease in C:N initial was not significant for sites with C:N$_{initial}$ below the median, and no change 0 ± 1% for sites in the lowest quarter of C:N$_{initial}$. Linear regression in Fig. 4 indicates that C:N$_{final}$ can be predicted from C:N$_{initial}$.

4. Discussion

Our previous report of losses of soil C and N focussed predominantly on pasture intensively grazed by dairy cows (Schipper et al., 2007). The additional profiles sampled in the current study allowed us to demonstrate that changes in soil C and N in grassland differed between land uses and slope classes. Losses occurred under intensive dairy grazing, while gains were measured in hill country during the period of study that ranged from 1967 when the first samples were collected to 2010 when the last samples were collected. On average, soils were resampled 27 years after the first sampling which took place generally in the early 1980s. There were no significant changes in C and N under drystock grazing on flat land or on tussock grasslands in high country.

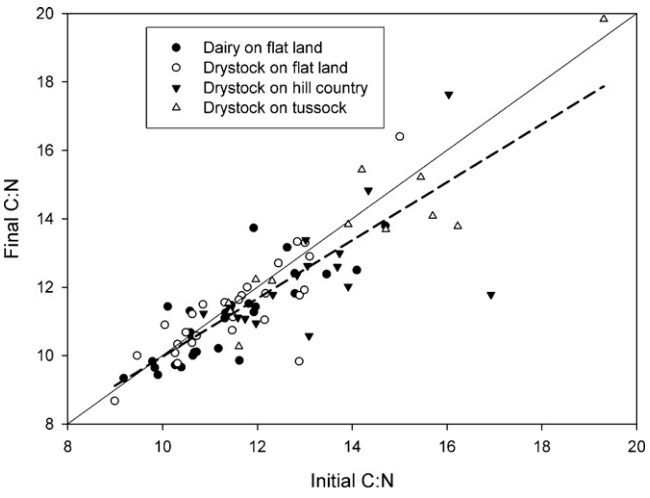

Fig. 4. The general decrease in C:N ratio between sampling times of top 30 cm of profile. Solid line is a 1:1 line and dashed line is regression fit (adjusted $R^2 = 0.72$, $n = 83$, $P < 0.001$).

4.1. Changes in soil C and N on flat land

Soils on flat land under dairy grazing lost C and N while land grazed by drystock did not change. This pattern suggests that the reasons for losses were associated with differences in management practices between these land uses. An alternative hypothesis would be that recent changes in climate differed between the spatial locations of dairy and drystock grazing and could be responsible for the different changes in soil C and N temporal dynamics. However, there was considerable spatial overlap of these two grazing practices (Fig. 1) suggesting this hypothesis was unlikely.

Generally, there has been a greater intensification in management of dairy land than land under drystock, particularly during the period from 1990 to 2005 (Parfitt et al., 2006, 2008) resulting in a number of differences in the pasture and stock management. Dry matter production of dairy grazed pastures is usually greater to support higher animal stocking rates. The greater aboveground dry matter production is achieved through increased inputs (e.g., N fertiliser) and more intensive pasture utilisation. In general, Conant et al. (2001) demonstrated that soil C increased with improved grassland management practices, such as fertilisation and irrigation, presumably by increasing C inputs from photosynthesis more than C losses from ecosystem respiration. In New Zealand, dairy pasture soils already had high levels of C when they were first sampled so they may differ from the studies described by Conant et al. (2001). Certainly, dairy systems have received greater N fertiliser inputs (50–150 kg N ha^{-1} y^{-1}) than drystock systems (our sites tended to receive no urea) since 1990, and Khan et al. (2007) proposed N fertiliser could decrease soil C, although there is evidence to the contrary (Reid, 2008; Zhang et al., 2010). Animal urine has a high pH and it may mobilise soil organic matter; this effect would be greater under dairy cows than in drystock systems because dairy cows produce large urine spots with high concentrations of N. Urine can leach to the lower soil profile and potentially explain loss of soil

C through-out the soil profiles (Lovell and Jarvis, 1996). It is unclear whether intensification on dairy land has led to changes in inputs of below-ground C that might also contribute to declining soil C contents but this is worth further investigation along with the other potential mechanisms discussed above.

There are only few regional scale studies of temporal changes in soil C and N in temperate grazed pastures with most studies focussing on cropping management or land use change. In Belgium, Meersmans et al. (2009) measured large declines in soil C in wet to extremely wet pasture soil and gains in drier pasture soils. They attributed the loss in wetter pastures to increased drainage and oxidation of organic matter and the increases in soil C in drier pastures were attributed to increased manure inputs from elevated cattle stocking rates. Bellamy et al. (2005) also measured declines in soil C in grasslands in England and Wales, which was subsequently attributed to land use change including decreased manure inputs and more efficient removal of crop residues with about 10 to 20% of the loss attributed to climate change (Smith et al., 2007; Hopkins et al., 2009). In a survey of top-soils of New Zealand pastures, Tate et al. (1997) did not find any significant change in soil C. The differences between the current findings and the previous sampling of New Zealand pasture soils was likely due to the different decades in which sampling was conducted. Tate et al. (1997) sampled soils prior to wide-scale intensification of dairy farming (MacLeod and Moller, 2006) when stocking rates increased substantially. The findings of Tate et al. (1997) therefore could be compared to our "drystock on flat land" category where we measured no significant change in soil C and N. These findings were also in agreement with chronosequences studies of pastures under relatively low intensity grazing that had been converted from scrub (Jackman, 1964): soil C initially increased by more than 1 Mg C ha^{-1} y^{-1} for the first 5 years but rates of increase declined to less 100 kg ha^{-1} y^{-1} between years 25 and 50 until reaching a new steady state (Schipper and Sparling, 2010).

4.2. Hill country pastures and high country tussock grasslands

The gains in soil C and N measured in hill country pastures was in contrast to findings at one other study of hill country in New Zealand where soil C declined on average by 200 kg C ha^{-1} yr^{-1} for 15 years in the top 7.5 cm (Lambert et al., 2000); however, caution should be applied when extrapolating changes measured at a single site and for shallow depths. Soil C and N can vary significantly with time at specific sites without changing long-term steady state stocks (Parfitt et al., 2010b; Schipper et al., 2010). In a study of hill country in New Zealand, Schipper et al. (2010) measured relatively large increases in topsoil C for the first 6 years of the study followed by either no change (low slopes) or losses (on steep slopes) in C for the next 16 years. These changes were attributed to a series of summer droughts which substantially decreased biomass production in the second part of the study period. Parfitt et al. (2009, 2010b) found that, for topsoil under hill country pasture in New Zealand, soil C decreased significantly by 4–8% in only one year, which probably arose from an infestation of Porina moth caterpillars (*Wiseana* spp) that reduced C inputs, however, the soil C recovered in subsequent years.

The gains of C and N in grazed hill pastures might be explained by long-term accumulation of C and N following initial land clearance. Much of New Zealand hill country was converted from forest to pasture about 150 years ago and this was accompanied by large-scale erosion removing topsoil (Scott et al., 2006). The subsequent establishment of legume based pastures allows soil C and N to recover but this recovery can take many decades (Sparling et al., 2003; Page et al., 2004). Erosion and deposition can lead to enhanced soil C stocks where soil thickening occurs (Yoo et al., 2006). Although the sites were resampled at the same site and aspect and typically in upper or mid-slope hillslope positions, the possibility of net soil deposition cannot be ruled out and is worthy of further investigation.

In a study of soil organic matter changes in tussock grasslands, McIntosh et al. (1999) found that 19 years super-phosphate fertilisation increased soil C by 7 Mg ha^{-1} in comparison to unfertilised control paddocks. These authors attributed this increase in soil C and N to increased plant production and a decrease in bare areas. Our sites; however, generally had low intensity of grazing and this may explain the lack of change of soil total C and N pools.

4.3. Losses at different depths

Our data strongly support earlier findings that change in soil C and N can extend throughout the profile rather just in the top soil (Schipper et al., 2007; Franzluebbers and Stuedemann, 2009). Despite the apparent long mean residence times of soil C in deep horizons, studies have demonstrated that soil organic matter moves through horizons to 1 m depth more rapidly than previously thought (e.g., Baisden and Parfitt, 2007; Sanderman et al., 2008). Mean changes in soil C to 90 cm were 1.5 larger than changes in total C to 30 cm and changes in total N were 1.9 times greater summed to 90 cm than 30 cm. This suggests that a focus on solely the top 30 cm may not be appropriate when determining long-term changes in soil organic matter. However, simple linear regressions between changes at 30 cm and 90 cm were relatively strong and consequently, shallower sampling may be used to predict changes that are occurring deeper in the soil profile under pastures in New Zealand. Sampling only to shallow depths (e.g., 10 cm) can greatly underestimate actual changes.

4.4. Implications

There are several implications from these findings that are important at a national scale. The area for each land use category was obtained from data bases held at Landcare Research (www.landcareresearch.co.nz). These land areas were used to estimate total gains and losses of soil C and N for New Zealand grazed pastures for the top 30 cm (Table 3). The estimated change in C (-0.02 Tg C y^{-1}) needs to be treated cautiously because sampled profiles were not originally sited for developing a national inventory of long-term changes in soil organic matter. Caution is especially warranted in extrapolating results from hill country because of the diversity of soils present on catenas in this landform. However, assuming that the sites were representative of the land use/land form category, we found no net change in C under pastures for New Zealand because the losses from flat land were offset by sequestration in hill country. We note that the errors around this estimate are large; SEM of 1.0 Tg C y^{-1}.

As N is predominantly covalently bonded to C in soil organic matter it is not surprising that changes in N were highly correlated to changes in soil C. Similar relationships between changes in C and N were found in a grazing exclusion study by Piñeiro et al. (2009). However, C:N ratio declined between samplings indicating that the organic matter was becoming more N rich with time as immobilisation of N occurred even when the soil was losing C and N. This supports previous suggestions that soils under New Zealand pastures are approaching a point where the C:N ratio no longer decreases (Schipper et al., 2004).

This study has demonstrated that soil organic matter (C and N) has changed considerably for grazed pastures of New Zealand over the intervening 13–40 years. On average, significant amounts of soil C and N were lost under dairy grazing on flat land but were gained under drystock grazing on hill country. No significant changes in C and N were observed under drystock on flat land and under tussock grasses in high country. Key questions remain about whether losses and/or gains are continuing and the reasons for these losses.

Table 3
Change in total C and total N of grazed land for top 30 cm extrapolated across New Zealand.

Land form	Land use	Number of profiles	Area (million ha)	Total change (million T C y^{-1})	SEM (million T C y^{-1})	Total change (thousand T N y^{-1})	SEM (thousand T N y^{-1})
Flat	Drystock	27	3.9	−0.56	0.76	−30	46
Flat	Dairy	29	1.5	−1.09	0.24	−85	24
North Island hill	Drystock	15	3.1	1.62	0.57	206	56
South Island tussock	Drystock	12	2.6	0.00	0.34	11	23
Total		83	11.1	−0.02	1.04	103	80

The observed changes and the underlying mechanisms warrant further investigation due to their size and relevance to national C and N budgets. Our soil profile re-sampling approach differs markedly from, and complements, other possible approaches such as that of Bellamy et al. (2005) that have recently found large C changes at national scales. We recommend coherent and more expansive programmes targeting both resampling and studies of underlying mechanisms if soil C research is to make robust contributions to greenhouse gas mitigation and inclusion in emission trading systems. We initially thought that soil C might change less for Andisols than in other Soil Orders because Andisols sequester and protect C better than many other Soil Orders (Parfitt, 2009) but our data for 12 soils under dairying show that Andisols lose similar amounts of C to the other Soil Orders. Andisols lost 0.6 T ha^{-1} y^{-1} in the top 30 cm (full data not shown). Further investigation of the role of different Soil Orders in controlling land use effects on soil C and N is warranted. Moreover, there are potentially strong co-benefits are implied by the coupling between soil C and N changes: when 1 Mg C is sequestered or lost by soil, about 100 kg of N is gained or lost. Losses can be as reactive nitrogen such as nitrate, ammonia, and nitrous oxide causing a cascade of environmental impacts, but also as unreactive N_2.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.agee.2010.10.005.

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