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Accumulation of soil organic C and change in C:N ratio after establishment of pastures on reverted scrubland in New Zealand

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Abstract Rates of organic carbon accumulation and changes in C:N ratio are reported for 10 New Zealand soils converted to pastures from scrub. The data were derived from archive papers originally published in 1964, but which did not report on changes in the C contents of the soils. The soils had been sampled to 0–7.5, 7.5–15, and 15–30 cm depths and chronosequences of up to 66 years obtained by selecting sites with differing times since pasture establishment. We calculated changes in the mass of C and N in the 0–7.5 cm depth and compared that to the mass in the 0–30 cm depth of soil. The shortest time over which organic matter change was assessed was 18 years and the longest was 66 years. Nine of the ten soils showed increases in the C contents of the 0–7.5 cm depth soil, and a natural logarithmic curve generally gave a better fit to the time course data than a linear fit. However, when the full 0–30 cm depth was considered, only two soils showed a significant increase in total C, changes in the C contents of other soils were non-significant, and two soils showed a decline in total C. The rates of change in the C contents were averaged over 0–5 years, 5–25 years and 25–50 years. Across all 10 soils, the mean rates of accumulation of C in the 0–7.5 cm depth were 1.07 (between 0 and 5 years), 0.27 (between 5 and 25 years) and 0.09 Mg C ha^{-1} $year^{-1}$ (between 25 and 50 years) and significantly ($P < 0.05$) greater than zero. Very similar rates were obtained for the 0–30 cm depth of soil with mean rates across all soils 1.01 (0–5 years), 0.25 (5–25 years) and 0.09 Mg C ha^{-1} $year^{-1}$ (25–50 years), respectively. In the 0–7.5 cm depth of soil, total Kjeldahl N (TKN) increased significantly in seven of the 10 soils. When expressed for the 0–30 cm depth of soil, only five soils still showed significant increases in TKN contents over time. Using the data for the 0–7.5 cm depth, the predicted time (mean and standard error) for the soils to reach a C:N ratio of <10 was 46 ± 17 years. The soils were originally sampled over 44 years ago, suggesting that currently (2009), very few of them could be expected to have capacity for further N storage in organic matter in the surface soil unless there was an increase in soil C. Changes in soil C and N in the shallow upper soil layers are easily masked by the relatively small changes in C and N contents and much greater masses of soil at lower depths.

Keywords Soil organic C · N storage · Sequestration · Deforestation · Pasture chronosequence

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Introduction

There is renewed interest in the amounts of organic C and N in soil and their rates of accumulation and loss; both for the benefits that soil organic matter has on soil properties but also because of the large amounts of C and N sequestered in soil organic matter which has significance for global C and N balances. Organic matter accumulates slowly in soils, typically taking many decades or hundreds of years to reach equilibrium after disturbance (Powlson and Johnston 1994, Jenkinson et al. 1987; Gregorich and Carter 1997, Tate et al. 2005). This makes measuring accumulations and losses difficult and not suited to short-term monitoring. The very few long-term (>100 year) field experiments mainly in Britain and the USA have been used to calibrate C turnover models such as Rothamsted C (Jenkinson et al. 1987) and CENTURY (Parton et al. 1987). These models have been used to predict longer-term changes in organic matter contents of New Zealand soils (e.g., Parshotam and Hewitt 1993; Sparling et al. 2003a). However, there is a great paucity of New Zealand long-term data to validate the models, with most reports measuring C and N changes in soils only over 3–15 year periods and on a limited number of sites (e.g., Ross et al. 1982, 1984; Hart et al. 1999, Francis et al. 1999, Shepherd et al. 2001). Other authors have attempted to avoid the problem of long-term monitoring by identifying chronosequences of matched sites (Schipper et al. 2001; Sparling et al. 2003b) or resampling archive sites (e.g., Schipper et al. 2007). The major constraint of re-sampling sites or sampling chronosequences is that changes in land management are often poorly documented and determining causal drivers of changes in C and N can be masked by unknown management factors.

The amount of N stored in NZ agricultural soils has been steadily increasing and the C:N ratio declining over the past 150 years since the introduction of European agriculture (Sparling and Schipper 2004). On the assumption that the soil C:N ratio is unlikely to fall below 9 (Batjes 1996), and that many NZ pasture soils are not accumulating further C (Schipper et al. 2007), it appears that some NZ soils may be approaching maximum capacity to store N as organic matter (Schipper et al. 2004). Such soils are at greater risk of leaching inorganic and dissolved organic N to waters; and also contributing to N_2O fluxes through denitrification because of greater nitrate availability (Galloway et al. 2003; Conant et al. 2005).

During searches of New Zealand literature into long-term changes in soil organic matter, we became aware of two papers by Jackman (1964a, b) who reported organic matter changes in chronosequences of 10 New Zealand soils under introduced pasture. The soils had originally been cleared of indigenous native forest by European settlers between 1850 and 1900, with the intention of using the land for pastoral farming, but these original clearances had reverted to scrubland. The re-establishment of new pastures involved clearing the reverting scrubland, cropping for 1 year and resowing to new pasture. Jackman identified sites that had been resown at different times, establishing chronosequences on matched soils of up to 66 years after pasture renewal. Responding to topical issues for the time, Jackman (1964a, b) focused on N, P and S accumulation in the top 0–7.5 cm of the soil and availability of these nutrients during pasture development. However, he analysed the soil in three depths, 0–7.5, 7.5–15 and 15–30 cm, which allowed us to compare the surface 0–7.5 cm soil with the 0–30 cm depth often used to report on C stocks in soils. Concern has been expressed recently by Blanco-Canqui and Lal (2008) that changes in the surface soils may not reflect total changes in organic C and N storage in deeper soil profiles. Jackman did not calculate rates of change in soil C, but provided data on %C and bulk density in graphs and tables respectively. Pastoral agriculture accounts for about half of the land use in New Zealand (Parliamentary Commissioner for the Environment 2004), and these data seem to be one of the few longer-term data sets that could assist our understanding of how pasture management practices might influence national C accounting. With ongoing intensification for greater food production, there is increasing short-term cultivation of pasture to control weeds and to establish improved varieties of pasture grasses and clovers, and for winter fodder crops. The periodic cultivation could be expected initially to reduce soil C and N. Information on rates of organic matter recovery following occasional cultivation and pasture renewal is lacking for New Zealand and generally scarce globally (Conant et al. 2007). We have reworked Jackman's data to provide new estimates of the rates of accumulation of C and also an assessment of how much longer the soils can continue to accumulate N. We compare changes in the surface 0–7.5 cm depth with those over the 0–30 cm depth.

Materials and methods

Chronosequences of up to 66 years were identified for 10 soils, (7–19 samples in each chronosequence), where pastures were developed on land formerly in scrubland (Table 1). Site preparation was reported to be generally the same for all 10 soils. The land had been cleared from native broadleaf-podocarp forest some years earlier and converted to pasture. The pasture had subsequently reverted and the land colonised by scrub and weeds including gorse (*Ulex europea*), blackberry (*Ribes* spp.), bracken fern (*Pteridium aquilinum*) and manuka (*Leptospermum scoparium*). For pasture re-establishment, the sites were ploughed, stumps removed, sown to a crop (unspecified) for 1 year, re-ploughed and sown to ryegrass-white clover pasture. The nature of the site descriptions (ploughing and cropping prior to pasture) suggests the landform was rolling or flat and not at risk of erosion.

Soil samples were collected to 0–7.5, 7.5–15, and 15–30 cm depth using a 2 cm diameter auger. For each soil and depth, 12 replicate cores were bulked, air-dried at 35°C, and sieved <2 mm. A finely ground

Table 1 Soil names, number of samples, soil order, taxonomy, parent material, average rainfall, mean annual temperature, age of the chronosequence and brief land use history of the soils used in the study

Soil and number of samples in the chronosequence	Soil Order[a]	Soil taxonomy[b]	Parent material	Rainfall (mm)	Mean temperature (°C)	Age of chronosequence (year)	Land use history
Oropi sand (16)	Pumice	Vitric Hapludand	Rhyolitic pumice	1,905	12.2	46	Former pasture invaded by gorse was sown to annual pasture, ploughed and resown.
Taupo sandy silt (11)	Pumice	Vitrandic Udorhent	Rhyolitic pumice	1,143	11.1	26	Scrub and tussock were cleared from reverted land and resown to pasture
Tiniroto loamy sand (10)	Pumice	Vitric Hapludand	Rhyolitic pumice	1,524	12.2	18	Reverted pasture was cleared of bracken and blackberry, ploughed, cropped for 1 year and sown to pasture
Tirau sandy loam (18)	Allophanic	Typic Hapludand	Rhyolitic volcanic ash	1,270	13.3	66	Previous pasture was ploughed, cropped for 1 year and resown to pasture
New Plymouth brown loam (10)	Allophanic	Typic Hapludand	Andesitic volcanic ash	2,159	12.2	28	Previous pasture was ploughed, cropped for 1 year and resown to pasture
Egmont black/brown loam (7)	Allophanic	Typic Hapludand	Andesitic volcanic ash	1,219	12.2	19	Previous pasture was ploughed, cropped for 1 year and resown to pasture
Hamilton clay loam (13)	Granular	Humic Hapludult	Andesitic volcanic ash	1,347	13.8	29	Previous pasture was ploughed, cropped for 1 year and resown to pasture
Matapiro silt loam (18)	Pallic	Udic Haplustalf	Sandstone	889	12.2	44	Previous pasture was ploughed, cropped for 1 year and resown to pasture
Tokomaru silt loam (13)	Pallic	Typic Fragiaqualf	Loess	991	12.8	20	Previous pasture was ploughed, cropped for 1 year and resown to pasture
Waiotu friable clay (19)	Oxidic	Typic Hapludox	Basalt	1,524	13.8	45	Indigenous forest was cleared in 1916, stumps were removed, the land ploughed and resown to pasture.

[a] Hewitt (1998) and [b] Soil Survey Staff (2006)

Table 2 Soil, age of chronosequence, and curve fitting statistics for the accumulation of total C (Mg C ha^{-1}) in the 0–7.5 cm and 0–30 cm depth of soil after conversion from scrub to pasture

0–7.5 cm depth						0–30 cm depth			
Soil	Age (years)	A (slope)* and standard error	B (Intercept) and standard error	R^2	Significance *P*	A (slope)* and standard error	B (Intercept) and standard error	R^2	Significance *P*
Oropi	46	3.50 ± 0.71	36.5 ± 2.0	0.64	**<0.001**	−7.23 ± 1.60[a]	135.2 ± 4.4	0.63	**<0.001**
Taupo	26	6.63 ± 1.53	19.6 ± 3.2	0.68	**0.002**	2.96 ± 2.03	64.3 ± 4.3	0.19	0.179
Tiniroto	18	6.26 ± 1.18	26.2 ± 2.9	0.78	**<0.001**	7.59 ± 5.55	80.3 ± 13.7	0.20	0.189
Tirau	66	0.38 ± 0.44	48.7 ± 1.2	0.04	0.403	−2.67 ± 1.62[a]	116.8 ± 4.4	0.14	0.119
New Plymouth	28	1.36 ± 0.47	61.4 ± 1.3	0.51	**0.019**	6.03 ± 4.09	142.4 ± 11.1	0.21	0.179
Egmont	19	2.97 ± 0.977	49.0 ± 1.8	0.65	**0.028**	5.49 ± 2.82	128.5 ± 5.3	0.41	0.108
Hamilton	29	2.57 ± 0.817	30.3 ± 1.9	0.48	**0.008**	2.25 ± 2.71	73.7 ± 6.4	0.06	0.424
Matipiro	44	4.44 ± 1.037	24.9 ± 2.7	0.54	**<0.001**	6.23 ± 2.46	71.0 ± 6.5	0.29	**0.022**
Tokomaru	20	3.46 ± 0.46	30.8 ± 0.9	0.60	**0.002**	6.37 ± 1.36	77.2 ± 2.7	0.67	**<0.001**
Waiotu	45	3.46 ± 0.90	42.1 ± 2.3	0.46	**0.001**	4.13 ± 2.40	120.2 ± 6.0	0.17	0.128

Figures in *bold* type indicate a significant ($P < 0.05$) change in total C content

[a] Note negative slope, indicating a decline in total C

* To fit a logarithmic model $y = A \ln(x) + B$, where y = total C in Mg C ha^{-1}, x = time in years, and B is a constant (intercept). Only P values in *bold* are significant at $P < 0.05$

subsample was used for soil chemical analyses. Total C was measured using chromate oxidation and represents soil organic C. Total soil N was determined by Kjeldahl digestion.

Numerical data were extracted from figures presented in Jackman (1964a, b) using the DataThief III software (http://www.datathief.org/). The extracted data for %C, %N, sampling depth and bulk density were converted to SI units and the data expressed on a Mg ha^{-1} basis for the 0–7.5 cm, 7.5–15 cm and 15–30 cm depths. Jackman (1964a) presented only a single bulk density figure for each soil and depth, but stated specifically "The volume weights did not change significantly with pasture age". That was consistent with the report by Schipper et al. (2007) that there had been no change in soil bulk density in New Zealand pastures sampled 20–30 years apart. The masses of C and N for each sampled depth were summed to obtain the 0–30 cm depth for each of the 10 soils for each year sampled. The C:N ratios were also calculated for 0–30 cm depths. For each soil, the least squares curve fitting method was applied to determine whether significant change had occurred during the sampled period. Changes in C and N were determined for two soil depths: 0–7.5 cm and 0–30 cm, as inspection of the data suggested the surface layer was where most changes were occurring. Curve fitting to the time course data, error factors and significance were obtained using fixed nonlinear regression functions in Statistica V8 (StatSoft, Inc. 2002). We compared the fits of linear and natural logarithm. Only the logarithmic curve statistics are reported because for the majority of soils the logarithmic curve function gave a better fit to the data (higher R^2, and lower P values) than the linear model for both the 0–7.5 cm and 0–30 cm depths (Table 2). The curves were fitted to the function $y = A \ln(x) + B$, where y = Total C in Mg C ha^{-1}, x = time in years, and B is a constant. Changes in C and C:N ratio were considered significant when the slope was significantly different from zero (two-tailed test).

Results

Total C

The shortest time over which organic matter change was assessed was 18 years (Tiniroto) and the longest was 66 years (Tirau). Nine of the ten soils showed increases in the C contents of the 0–7.5 cm depth soil, but when those data were combined with the two deeper depths to obtain changes for the full 0–30 cm, only two soils (Matapiro and Tokomaru) showed a significant ($P < 0.05$) increase, changes in other soils were non-significant, and two soils (Oropi and Tirau) showed a loss in soil C (Table 2). A demonstration of the contrasting trend obtained for C accumulation from the 0–7.5 cm depth soil and the 0–30 cm depth soil is shown for the Oropi soil in Fig. 1.

As indicated from the logarithmic fit to the data, the rates of change in the C contents were not uniform but declined through time. Rates of accumulation were calculated as the averages over 0–5 years, 5–25 years and 25–50 years (Tables 3). For the 0–7.5 cm depth, the annual rates of increase between 0 and 5 years ranged from 0.12 Mg C ha^{-1} in the Tirau soil to 2.13 Mg C ha^{-1} in the Taupo soil. In general, the rates of accumulation between 5 and 25 years were around one quarter of those between 0 and 5 years and the rates at 25–50 years were about one tenth of those between 0 and 5 years.

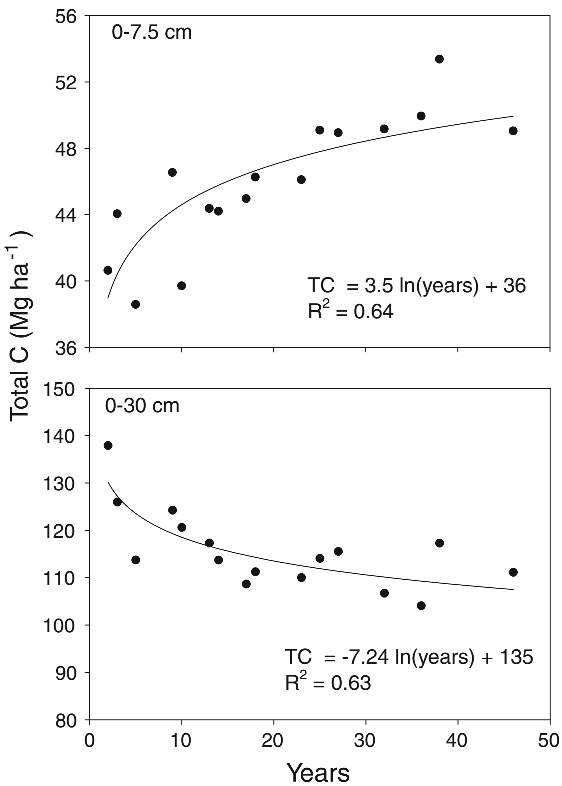

Fig. 1 An example of the contrasting trends in total C content of Oropi soil assessed by soil sampled to 7.5 cm or 30 cm along a chronosequence after conversion from scrub to pasture

Data are also presented for the 0–30 cm depth of soil although the fitted curves were generally non-significant and two soils (Oropi and Tirau) appeared to lose organic C over the chronosequence (Table 3). Annual rates of accumulation in the remaining soils ranged between 0.72 Mg C ha^{-1} (Hamilton soil) and 2.56 Mg C ha^{-1} (Tiniroto). Rates of C accumulation in the 0–30 cm depth declined with time in the same manner as the 0–7.5 cm depth samples (Table 3).

Averaged across all 10 soils, the rates of accumulation of C in the 0–7.5 cm depth were 1.07, 0.27 and 0.09 Mg C ha^{-1} year^{-1} for periods 0–5, 5–25 and 25–50 years, respectively, and these averages were significantly ($P < 0.05$) greater than zero. Very similar rates were obtained for the 0–30 cm depth of soil with mean rates across all soils for periods 0–5, 5–25 and 25–50 years being, 1.01, 0.25 and 0.09 Mg C ha^{-1} year^{-1}, respectively, and these averages were significantly greater ($P < 0.05$) than zero (Table 3). The similarity of the mean accumulation rates for the 0–7.5 cm depth soil and the 0–30 cm depth of soil suggested that virtually all the change in C content occurred in the 0–7.5 cm depth of soil.

Total N and C:N ratio

Data on total N were reported by Jackman (1964a, b) and are not repeated here. In the top 7.5 cm of soil there were significant increases in N contents over time of seven of the 10 soils, with Tirau, New Plymouth and Egmont showing non-significant change. When expressed for the 0–30 cm depth of soil, the same three soils, plus two others (Tiniroto and Tokomaru) showed no significant change in total N content.

The initial C:N ratios of the soils were generally low (data not presented). In general, the natural logarithmic function gave a better fit to the C:N ratio data than a linear function, indicating the rates of change over time were not uniform. For the 0–7.5 cm depth, seven of the 10 soils showed significant change, with two soils (Matipiro and Tokomaru) showing an *increase* in C:N ratio rather than the expected decrease (Table 4). Increasing the sample depth to 0–30 cm masked the changes in the surface 0–7.5 cm depth with only two soils (Oropi, and Tokomaru) showing a significant change in C:N ratio. Three soils, Tirau, New Plymouth and Waiotu all showed an *increase* in C:N ratio; however, these soils all started

Table 3 Rates of accumulation or loss in total C in 0–7.5 cm and 0–30 cm depths of 10 New Zealand soils estimated at 0–5, 5–25 and 25–50 years after re-establishing pastures on former scrubland land

Soil	Rate of C accumulation (Mg C ha^{-1} $year^{-1}$)					
	0–7.5 cm depth			0–30 cm depth		
	0–5 years	5–25 years	25–50 years	0–5 years	5–25 years	25–50 years
Oropi	1.13	0.28	0.10	−2.33	−0.58	−0.20
Taupo	2.13	0.53	0.18	0.95	0.24	0.08
Tiniroto	2.01	0.50	0.17	2.56	0.64	0.22
Tirau	0.12	0.03	0.01	−0.86	−0.21	−0.07
New Plymouth	0.44	0.11	0.04	1.94	0.49	0.17
Egmont	0.96	0.24	0.08	1.77	0.44	0.15
Hamilton	0.83	0.21	0.07	0.72	0.18	0.06
Matipiro	1.43	0.36	0.12	2.01	0.50	0.17
Tokomaru	0.59	0.15	0.05	2.05	0.51	0.18
Waiotu	1.11	0.28	0.10	1.33	0.33	0.11
Mean	**1.07**	**0.27**	**0.09**	**1.01**	**0.25**	**0.09**
Std Error	0.20	0.05	0.02	0.48	0.12	0.04

Negative numbers indicate a *decrease* in total C over the sampled period. Mean values in *bold* were significantly different from zero ($P < 0.05$)

Table 4 Average annual rates of change in soil C:N ratio in 0–7.5 cm and 0–30 cm depths of 10 New Zealand soils estimated at 0–5, 5–25 and 25–50 years after re-establishing pastures on reverted land

Soil	Annual rate of change					
	0–7.5 cm depth			0–30 cm depth		
	0–5 years	5–25 years	25–50 years	0–5 years	5–25 years	25–50 years
Oropi	−0.520	−0.130	0.104	−0.637	−0.159	−0.055
Taupo	−0.288	−0.072	0.058	−0.189	−0.047	−0.016
Tiniroto	−0.263	−0.066	0.053	−0.258	−0.065	−0.022
Tirau	−0.025	−0.006	0.005	0.023	0.006	0.002
New Plymouth	−0.032	−0.008	0.006	0.025	0.006	0.002
Egmont	−0.025	−0.006	0.005	−0.020	−0.005	−0.002
Hamilton	−0.158	−0.040	0.032	−0.144	−0.036	−0.012
Matipiro	0.075	0.019	−0.015	−0.042	−0.011	−0.004
Tokomaru	−0.122	−0.030	0.024	−0.060	−0.015	−0.005
Waiotu	0.025	0.006	−0.005	0.187	0.047	0.016
Mean	**−0.133**	**−0.033**	**0.027**	−0.112	−0.028	−0.010
Std. error	0.057	0.014	0.011	0.070	0.018	0.006

Negative numbers indicate a decrease in C:N ratio (an increase in N content and/or a decrease in C content) over the chronosequence. Mean values in *bold* were significantly different from zero ($P < 0.05$)

with extremely low C:N ratios that were close to 10 even at the establishment of pasture.

Despite the lack of significant change in C:N ratio in most individual soils, when the data from all soils were combined, a plot of the rate of change in the C:N ratio against the starting C:N ratio (modeled from the fitted curve) showed a strong linear trend, and indicated that those soils with higher initial C:N ratios showed a more rapid decrease in C:N ratio (Fig. 2).

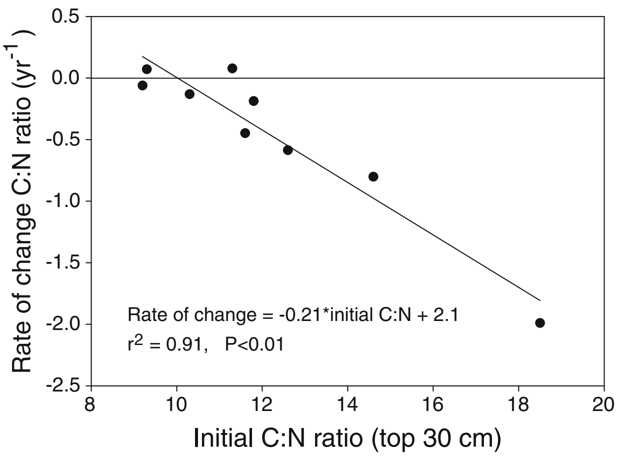

Fig. 2 The relationship between the rate of change (decrease) in the soil C:N ratio following pasture establishment, and the initial C:N ratio of the soil (0–30 cm depth)

We calculated how many years it would take the soils to reach a C:N ratio of <10 to meet our criterion of being unable to store further N in the organic matter pool, assuming that soil C had reached a steady state or only very slowly changing (as was indicated for the majority of reanalyzed soil chronosequences). Two of the soils (Taupo and Egmont) already had a C:N ratio <10 at the start of the chronosequence. It was not possible to make the calculation for Tokomaru soil because the C:N ratio rose over the chronosequence and so would never reach a C:N ratio of <10. Excluding the Tokomaru soil and using the data for the 0–7.5 cm depth, the predicted time (mean and standard error) for the soils to reach a C:N ratio of <10 was 46 ± 17 years. The soils were sampled over 45 years ago, suggesting that if those initial trends have continued, then the prediction for their present state (2009), would be that only three of the soils (Oropi, Tiniroto and Waiotu) would have any capacity for further N storage in organic matter in the surface soil.

Discussion

Changes in total C and N and C:N ratio along the chronosequences were readily detectable in the 0–7.5 depth of re-established pasture soil: usually the C content increased and the C:N ratio decreased. However, for individual soils, these changes were often not significant when calculated over the 0–30 cm depth. This was because the changes in the surface layer were masked by no detectable change or contrary changes in the deeper depths. Tate et al. (1997) sampled 43 New Zealand pasture sites that had initially been measured some 40 years earlier. They reported no change in total C contents of the surface soil since the earlier sampling, except for two organic soils that had been drained. However, as shown from the Jackman data often the majority of the change occurs in the initial years after pasture establishment, and the rate of C accumulation declines with time. The ability to detect change will depend very much on the time since the original sampling, spatial homogeneity of the soil and the intensity of sampling. Data also needs to be corrected if there have been any changes in soil bulk density.

The ability to be able to accurately measure soil C contents at field and national scales is important for national carbon accounting. Conant and Paustian (2002) examined spatial variability in pastures and concluded that over 5–10 year periods, and for a field scale study, between 14 and 28 samples would be adequate to detect changes greater than 2.3 Mg C ha^{-1}. That intensity of sampling is similar to that used by Jackman (1964a). Even so, we were not able to demonstrate consistent changes in organic C and N when using the 0–30 cm depth data, although changes were clear in the 0–7.5 cm depth. Blanco-Canqui and Lal (2008) warned against drawing conclusions about C storage based only on the top 0–10 depth of soil, and recommended the soil profile be sampled down to 60 cm. When that was done, Blanco-Canqui and Lal (2008) reported that there was often no significant difference in total C storage in the 0–60 cm profiles between conventional and no-till management, despite no-till management often being advocated for increased C sequestration. We concur that the methodologies to assess C storage in soils need careful scrutiny, particularly for the deeper soil horizons which can have the effect of masking changes in the surface horizons, as found in our reworking of Jackman's data.

By combining the data for all 10 chronosequences we were able to show significant change in organic C and N storage through time. The overall rates of change in total C, for the 0–7.5 cm depth and the 0–30 cm depth were very similar, suggesting that on these pasture soils virtually all the change in total C was happening in the surface layer. The average rates of accumulation of total C under pastures were about 1.0 Mg C ha^{-1} $year^{-1}$ for the first 5 years after conversion and about 0.25 Mg C ha^{-1} $year^{-1}$ between 5 and 25 years, which are similar to rates of change estimated in other shorter term studies on New Zealand soils. For example, we calculated that the chronosequences sampled by Jackman (1964a) had accumulated an extra 13.5 Mg C ha^{-1} (0–30 cm) 50 years after conversion from scrub to pasture. This value is very similar to the overall increase of 12 Mg C ha^{-1} calculated by Tate et al. (2005) for the additional C storage in improved New Zealand pasture soils converted from scrub. Conant et al. (2001) reported average rates of C accumulation of 0.35 Mg C ha^{-1} $year^{-1}$ after conversion of native vegetation to pasture; and 3.04 Mg C ha^{-1} $year^{-1}$ for pastures with the introduction of improved grass species (dates after conversions not specified). Walker et al. (1959) reported an initial C accumulation of 0.125 Mg C ha^{-1} $year^{-1}$ in the top 20 cm (averaged over 25 years) following conversion of New Zealand indigenous forests to pasture. However, the accumulation reported by Walker (1959) may be an overestimate because sampling was not done on an equivalent soil mass basis and soil mass in the top 20 cm had increased from 846 to 1,236 t ha^{-1} through the chronosequence.

We noted some discrepancies between our calculated values for C accumulation from the Jackman (1964a, b) papers, and those reported in a paper by Conant et al. (2005). These authors also reworked Jackman's data and presented a single rate of C sequestration for each soil. Their range of values (0.1–0.89 Mg C ha^{-1} $year^{-1}$) is similar to ours, but none of the values for each soil coincides with our own, and they reported increases for all soils whereas we found two soils had significant *decreases* over time. Conant et al. (2005) do not fully describe the method used to obtain their figures, and at present we are not able to explain this discrepancy.

Most studies of C storage in New Zealand pastures completed between 1950 and 1990 suggest that contents were at a steady state (see review by Tate et al. 1997). However, more recent research (Schipper et al. 2007) suggest that this may no longer be the case, particularly with pastures that are now under much more intensive management with greater inputs of fertilizer, higher stocking rates and larger inputs of animal feed (Parliamentary Commissioner for the Environment 2004). Some pastures soils had a substantial loss of soil organic C and N of up to 1.06 Mg C ha^{-1} $year^{-1}$ and 0.091 Mg N ha^{-1} $year^{-1}$ since sampled 17–30 years earlier (Schipper et al. 2007). Thus, it may be the case that the original pastures sampled by Jackman (1964a, b) over 40 years earlier, could now be losing C rather than accumulating, particularly if they are under intensive pastoral farming. To date, we have not been able to locate the original sites to verify this conjecture.

The C:N ratio of most soils in the Jackman data set declined, but only when measured in the 0–7.5 cm depth, or by combining data (0–30 cm) from all 10 chronosequences. Declines in C:N ratio were dependent on the starting C:N ratio (Fig. 2) with soils with initially higher C:N ratios accumulating N faster than soil with a low C:N ratio. Schipper et al. (2004) suggested that at accumulation rates of 50 kg N ha^{-1} $year^{-1}$, and a minimum C:N ratio < 10, then about half of the New Zealand soils surveyed would reach their capacity to store further N in organic matter within 50 years. The data from Jackman (1964a) supports this suggestion. The current trend for increased N loading to intensively used pastures in New Zealand indicates that the loss of capacity to store further N as organic matter may occur even sooner than the calculation suggests. The above argument assumes that soil C does not change. If soil C increases further N could be stored; for every 1 t ha^{-1} of additional C stored about 0.1 t ha^{-1} of N could be stored.

In general, the reanalysis of Jackman's original chronosequence data confirmed the traditional view (Tate et al. 1997, 2005) that conversion of native vegetation to pasture results in initially rapid accumulation of soil C and N and within 20 years reaches a new steady state after which C changes only slowly or not at all. In two cases, soils appeared to lose soil C in the longer term. However, these changes occur predominantly in the surface soil and when sampled to deeper depths, it was difficult to detect change in total C content of the profile. This steady state applies to pastures under lower intensity farming than much of contemporary dairy farming practice and there is evidence that soils under intensive farming have lost C and N in the past few decades (Schipper et al., 2007). In Jackman's chronosequences, changes in N were proportionally greater than changes in C resulting in declines in C:N ratio in soils that had initially higher C:N ratios. The decline in C:N ratio of these soils suggests that New Zealand soils are reaching a point where net immobilization of N into soil organic matter will no longer occur unless there are further increases in soil C.

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References

Batjes NH (1996) Total carbon and nitrogen in soils of the world. Eur J Soil Sci 47:151–163

Blanco-Canqui H, Lal R (2008) No tillage and soil profile carbon sequestration: an on-farm assessment. Soil Sci Soc Am J 72:693–701

Conant RT, Paustian K (2002) Spatial variability of soil organic carbon in grasslands: implications for detecting change at different scales. Environ Pollut 116:S127–S135

Conant RT, Paustian K, Elliott T (2001) Grassland management and conversion into grassland: effects on soil carbon. Ecol Appl 11:343–355

Conant RT, Paustian KP, Del Grosso SJ, Parton W (2005) Nitrogen pools and fluxes in grassland soils sequestering carbon. Nutr Cycl Agroecosyst 71:239–248

Conant RT, Easter M, Paustian K, Swan A, Williams S (2007) Impacts of periodic tillage on soil C stocks: a synthesis. Soil Tillage Res 95:1–10

Francis GS, Tabley FJ, White KM (1999) Restorative crops for the amelioration of degraded soil conditions in New Zealand. Aust J Soil Res 37:1017–1034

Galloway JN, Aber JD, Erisman JW, Speitsinger SP, Howarth RW, Cowing EB, Cosby BJ (2003) The nitrogen cascade. Bioscience 53:341–356

Gregorich EG, Carter MR (1997) Soil quality for crop production and ecosystem health. Developments in Soil Science 25. Elsevier, Amsterdam

Hart PBS, West AW, Kings JA, Watts HM, Howe JC (1999) Land restoration management after topsoil mining and implications for restoration policy guidelines in New Zealand. Land Degrad Dev 10:435–453

Hewitt AE (1998) New Zealand soil classification. Manaaki Whenua Press, Landcare Research, Lincoln

Jackman RH (1964a) Accumulation of organic matter in some New Zealand soils under permanent pasture. I. Patterns of change of organic carbon, nitrogen, sulphur and phosphorus. N Z J Agric Res 7:445–471

Jackman RH (1964b) Accumulation of organic matter in some New Zealand soils under permanent pasture. II. Rates of mineralization of organic matter and the supply of available nutrients. N Z J Agric Res 7:472–479

Jenkinson D, Hart PBS, Rayner JH, Parry LC (1987) Modelling the turnover of organic matter in long-term experiments at Rothamsted. INTECOL Bull 15:1–8

Parliamentary Commissioner for the Environment (2004) Growing for good. Intensive farming, sustainability and the New Zealand environment. Parliamentary Commissioner for the Environment, Wellington, 236 pp

Parshotam A, Hewitt AE (1993) Application of the Rothamsted carbon turnover model to soils in degraded semi-arid land in New Zealand. Environ Int 21:693–697

Parton WJ, Schimel DS, Cole CV, Ojima DS (1987) Analysis of factors controlling soil organic matter levels in Great Plains grasslands. Soil Sci Soc Am J 51:173–1179

Powlson DS, Johnston AE (1994) Long-term field experiments: their importance in understanding sustainable land use. In: Greenland DJ, Szabolcs I (eds) Chapter 22 in Soil resilience and sustainable land use. CAB International, Wallingford, pp 367–394

Ross DJ, Speir TW, Tate KR, Cairns A, Meyrick KF, Pansier EA (1982) Restoration of pasture after topsoil removal effects on soil carbon and nitrogen mineralisation, microbial biomass and enzyme activities. Soil Biol Biochem 14:575–581

Ross DJ, Speir TW, Tate KR, Cowling JC, Watts HM (1984) Restoration of pasture after topsoil removal: changes in soil biochemical properties over a 5-year period - a note. N Z J Sci 27:419–422

Schipper LA, Degens BP, Sparling GP, Duncan L (2001) Changes in microbial heterotrophic diversity along five plant successional sequences. Soil Biol Biochem 33:2093–2103

Schipper LA, Percival HJ, Sparling GP (2004) An approach for estimating maximum nitrogen storage in soils. Soil Use Manag 20:281–286

Schipper LA, Baisden WT, Parfitt RL, Ross C, Claydon JJ, Arnold G (2007) Large losses of soil C and N from soil profiles under pasture in New Zealand during the past 20 years. Glob Change Biol 13:1138–1144

Shepherd TG, Saggar S, Newman RH, Ross CW, Dando JL (2001) Tillage-induced changes to soil structure and organic carbon fractions in New Zealand soils. Aust J Soil Res 39:465–489

Soil Survey Staff (2006) Keys to soil taxonomy, 10th edn. US Department of Agriculture-NRCS, Washington, DC

Sparling GP, Schipper LA (2004) Soil quality monitoring in New Zealand: trends and issues arising from a broadscale survey agriculture. Ecosyst Environ 104:545–552

Sparling G, Parfitt RL, Hewitt AE, Schipper LA (2003a) Three approaches to define desired soil organic matter contents. J Environ Qual 32:760–766

Sparling G, Ross D, Trustrum N, Arnold G, West A, Speir T, Schipper L (2003b) Recovery of topsoil characteristics after landslip erosion in dry hill country of New Zealand, and a test of the space for time hypothesis. Soil Biol Biochem 35:1575–1586

StatSoft, Inc (2002) STATISTICA for Windows [Computer program manual]. Tulsa, OK, USA

Tate KR, Giltrap DJ, Claydon JJ, Newsome PF, Atkinson IAE, Taylor MD, Lee R (1997) Organic carbon stocks in New Zealand's terrestrial ecosystems. J R Soc N Z 27:315–335

Tate KR, Wilde RH, Giltrap DJ, Baisden WT, Saggar S, Trustrum NA, Scott NA, Barton JP (2005) Soil organic carbon stocks and flows in New Zealand: system development, measurement and modeling. Can J Soil Sci 85:481–489

Walker TW, Thapa BK, Adams AFR (1959) Studies on soil organic matter: 3. Accumulation of carbon nitrogen, sulfur, organic and total phosphorus in improved grassland soils. Soil Sci 87:135–140