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Changes in soil total C and N contents at three chronosequences after conversion from plantation pine forest to dairy pasture on a New Zealand Pumice soil

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Abstract. The large amounts of carbon (C) and nitrogen (N) sequestered as organic matter in soils have implications for global and national C and N balances and greenhouse gas emissions. Changes in soil management can affect the amount of C and N stored in soil. We investigated the change in land use from radiata pine plantation to ryegrass–white clover dairy pasture on the total C and N content of Taupo Pumice Soil. Samples were taken at three study sites (Atiamuri, Tokoroa and Wairakei) in North Island, New Zealand. Soils were cored to 60 cm depth and subsampled by soil horizon, and bulk density cores were taken from soil pits. A chronosequence of sites was obtained after conversion from pines to pasture. Long-term pastures (40–80 years) and mature pine plantations were included for further comparison. Regression analyses were completed after logarithmic transformation of the time data. The data were highly variable, but significant ($P < 0.05$) increases in total C and N were found at the Atiamuri and Wairakei sites. However, there was no significant change in the total C content of the profile at the Tokoroa site. Increases in total C and N were greatest in the Ap horizon and were most rapid 1–5 years after conversion. Overall rates of increase in the first 10 years after conversion were 0.167 kg C m^{-2} $year^{-1}$ for total C and 0.032 kg N m^{-2} $year^{-1}$ for total N, dropping to 0.027 kg C and 0.005 kg N m^{-2} $year^{-1}$ for the 10–50-year period. The change in land use from plantation forest to dairy pasture has resulted in a moderate increase or no change in soil storage of C. Compared with total C, increases in total N storage were proportionately greater in all three examples of this Taupo Pumice Soil.

Additional keywords: deforestation, land use change, pasture chronosequence, soil carbon, soil N, soil storage.

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Introduction

There is increased interest in the amounts of carbon (C) and nitrogen (N) stored in soils, not only because of the benefits of organic matter on soil nutrient dynamics and physical condition, but also because soils form a very large terrestrial reservoir which can affect national and global C and N budgets, with implications for greenhouse gas emissions and climate change (Amundson 2001; Murty *et al*. 2002). The amounts of C and N stored in soils are affected by land use and management (Conant *et al*. 2001; Schipper *et al*. 2007; Poeplau *et al*. 2011; Hewitt *et al*. 2012), and for soils with initially low contents of C and N, there is the potential that under appropriate management, soils could accumulate C and N and reduce net emissions to the atmosphere (Paustian *et al*. 1997; Lal 2001). In a global context, New Zealand topsoils are generally high in organic matter because of the underlying geology, maritime climate, the limited amount of arable farming, and extensive permanent pastures, combined with plantation forestry and considerable residual indigenous forest (Tate *et al*. 1997).

The amount of plantation forest in New Zealand is relatively small, mainly *Pinus radiata* (D.Don) covering ~6.6% of the land surface (1.7 Mha), with about one-third of the planted area on pumice soils in the central North Island (MAF 2011). However, the amount of plantation forest is important because forests planted (and retained) since 1990 are regarded as C sinks under the first commitment period of the Kyoto Protocol (Ministry for the Environment 2009). The central North Island pumice soils were originally cleared of native vegetation by European settlers around 1920–1930 for pastoral farming and forestry. Some pine forests are now in their second or third rotation. During the 1980s and 1990s, some of these pastures were converted to plantation forests in the hope of improved financial returns (Beets *et al*. 2002). However, the financial returns from forestry have not met expectations, and there has been a large increase in the returns from dairy farming. Consequently, existing plantation forests are now being converted to dairy pasture following the harvesting of mature trees, and even partly grown trees have been removed and replaced by pasture for dairy farming (Forest Owners Association 2013). This change from plantation forests to pasture has potential implications for C and N stocks in soil organic matter, as well as stocks stored in biomass and litter.

In several reviews, authors have attempted to summarise effects of changing land use on soil C and N contents (Conant *et al*. 2001; Murty *et al*. 2002; Schipper *et al*. 2007; Poeplau *et al*. 2011). The authors stress the difficulty in making such compilations because of the different sampling methods used around the world, the frequent absence of bulk density data to allow correct land use comparisons, natural soil variability, and inconsistency in the soil depths sampled. There were also very few examples of the land use change from plantation forest to pasture. Murty *et al*. (2002) reported that overall they were not able to detect any clear trend in the C content of soils when converting from indigenous forest to pasture. Working with data from temperate-zone regions, Conant *et al*. (2001) noted that where grasslands were reseeded, fertilised, and managed with a lenient grazing regime, there were usually increases in the C in soils under pasture.

Several studies have compared the organic C and N contents of New Zealand soils used for plantation forestry or pasture. However, most of these studies were single paired comparisons of mature pine forests and established permanent pastures (Giddens *et al*. 1997; Davis and Condron 2002) and only sampled to 7.5 or 15 cm (Giddens *et al*. 1997; Sparling and Schipper 2004; Hedley *et al*. 2009). Single sample comparisons do not allow rates and patterns of change to be calculated. Hedley *et al*. (2009) used a chronosequence of pasture sites, but the sequences were only 1–5 years after conversion from plantation forestry to pasture, and there were no long-term forestry sites against which to compare the converted pasture. Davis and Condron (2002) suggested that where sites were converted from pasture to forest (the reverse process), at least 10 years would be required before any substantial change in soil C stock would be detected. Because of the considerable soil disturbance caused by removing trees, windrowing and recontouring, Hedley *et al*. (2009) recommended that soil sampling of converted pastures should be to at least 30 cm. Hewitt *et al*. (2012) used sampling to 30 cm depth for paired-site comparisons of radiata pine plantations and low productivity grassland, but Blanco-Canqui and Lal (2008) recommended sampling to 60 cm depth for comparison of tillage methods to conserve soil C. A complication in sampling to greater depth is that soils from the B and C horizons contain much less C, and often show greater variability in C content (Franzluebbers 2009) and relatively small change in C and N concentrations (Poeplau *et al*. 2011). When the whole soil profile is combined, changes in C and N contents between treatments may be non-significant, despite relatively large changes in the surface horizon (Kravchenko and Robertson 2011; Schipper and Sparling 2011).

We attempted to measure the amounts and rates of change in the total C and N contents of three different study areas on a pumice soil undergoing land-use change from long-term plantation forestry to dairy pasture in central North Island, New Zealand. Our hypothesis was that land use change from plantation pine to pasture would result in a change in total C and N sequestered in this pumice soil. We further hypothesised that the greater the length of time since conversion, then the greater the amounts of C and N that would be stored in soil. Chronosequences of sites after land-use change were sampled by soil horizon down to 60 cm depth. Sites under long-term pine forest and dairy pasture were also included to provide reference points for potential long-term C and N storage in soil and the pattern and rates of change.

Materials and methods

Site selection and management

Chronosequences of sites were selected on dairy farms that had been converted from long-term pine plantation (second- and third-rotation *Pinus radiata*) to dairy pasture in central North Island, New Zealand. The three study areas, Atiamuri, Tokoroa and Wairakei, were all on Taupo Pumice Soil (Hewitt 2010) formed from pyroclastic Taupo Pumice parent material (rhyolitic composition) deposited around 232 CE (Hogg *et al*. 2012). Approximate USDA Soil Taxonomy equivalents (Soil Survey Staff 2010) are Vitrands, Vitraquands and Vitricryands. For maps of the areas and transect and pit locations see Lewis (2011): http://researchcommons.waikato.ac.nz/handle/10289/5749. Each of the three study areas included a range of times since conversion from pine plantation to pasture and examples of long-term (second- or third-rotation) pine plantation and long-term pasture (40–80 years) (Table 1). Converting forestry land to dairy pasture involved felling and harvesting mature trees; smaller, non-mature trees were removed by bulldozers. Following removal of the pine trees at Tokoroa and Atiamuri, the soil was disc-cultivated, harrowed, rolled, and then seeded. At Wairakei, heavy-duty mulchers were first used to break up remaining wood on or in the surface soil (excluding that deposited in windrows and slash heaps), and then the land was harrowed, rolled and seeded. Farm units followed a similar fertiliser regime, with ~200 kg N ha^{-1} $year^{-1}$ applied in spring and autumn. Phosphorus and potassium were added as

Table 1. Land use, years since conversion from plantation pine to pasture, and number of replicate paddocks sampled in the three study areas (Atiamuri, Tokoroa and Wairakei) on Taupo Pumice Soil in North Island, New Zealand

Study area	Land use	Time (years) since conversion from pines	Replicate paddocks
Atiamuri	Mature pine forest	–	1
	Dairy pasture	2	2
	Dairy pasture	5	2
	Dairy pasture	11	3
	Long-term dairy pasture	80	3
Tokoroa	Mature pine forest	–	1
	Dairy pasture	2	1
	Dairy pasture	3	1
	Dairy pasture	5	1
	Long-term dairy pasture	40	3
	Long-term sheep–beef pasture	50	3
Wairakei	Mature pine forest	–	1
	Dairy pasture	2.5	3
	Dairy pasture	3	3
	Dairy pasture	4	3
	Dairy pasture	4.5	1
	Long-term dairy pasture A	60	3
	Long-term dairy pasture B	40	3

required when regular soil testing indicated maintenance dressing was needed (Lewis 2011).

Our intention had been to obtain, for each of the study areas, three replicate sites for each time since conversion, with as many points as possible along a chronosequence of land use change from existing plantation forest to long-term dairy pasture. In practice, this meant taking soil samples from multiple farms in each study area, although in many cases, the farms were owned by a single large business or corporation and the individual farms operated as separate units with similar management (Lewis 2011). To permit comparison of sites at different stages since conversion, sampling transects were selected on areas that were of similar aspect and topography and likely to have similar soil profiles. At the Tokoroa study area, a remnant terrace landform was identified and all samples were taken from the terrace landform. The Atiamuri and Wairakei study areas were both reasonably flat and all sampling was done on flat land, making an effort to avoid small ridges in paddocks. All three of the study areas either had, or still have, windrows and slash heaps. On all study areas where windrows and slash heaps still exist, or were present in the past, an effort was made to keep soil pits and the transect clear from them, as the soil was more likely to have had greater disturbance and was also more likely have an abundance of woody plant material.

It was not possible to obtain true replicate paddock transects (i.e. each transect in a separate paddock within a farm) for all of the chronosequences. In those cases where only one or two separate paddocks were available, then three transects were obtained from the single paddock and duplicate transects from the pair. The Tokoroa and Wairakei chronosequences were 60 km apart, with Atiamuri between them. At Atiamuri all sampling sites were within 3.5 km of each other, and at Wairakei they were within 10 km of each other, with most ~5 km apart. All long-term forest transects were from a single forest block at each site. For the basis of this report, for each period since conversion, any such pseudo-replicate data (three transects from a single paddock) were averaged before statistical analysis and presentation in Figures (Table 1). Precise georeferenced locations of all sampling points and soil pits are available in Lewis (2011): http://researchcommons.waikato.ac.nz/handle/10289/5749. Annual rainfall (~1300 mm) and average air temperature (~12°C) were similar at all three sites.

Soil sampling

Soil sampling occurred between March and July 2010. At each study area, for each point in the chronosequences, three transects 50 m in length were laid out, and samples were taken at seven random intervals along each transect.

Soil samples for C and N analysis were taken to 60 cm depth using a hand-driven tube corer and mallet (cores were 2.5 cm in diameter). For each transect, core samples were split into individual soil horizons, depths recorded for each soil horizon, and samples from the seven cores bulked according to horizon. In general terms, the horizons were Ap 0–15 cm, Bw 15–30 cm and Cu 30–60+ cm. At the Tokoroa site there was typically a buried A horizon (paleosol) starting at ~50 cm depth. Although this horizon was sampled (cores were taken to 60 cm), we later decided not to include this buried horizon, because the high relic C and N concentrations at depth were likely to mask any differences driven by land-use change in other parts of the profile. Therefore, the full profile data for the Tokoroa site are to only 50 cm, compared with 60 cm sampled at the Atiamuri and Wairakei study sites. However, at those sites, at the base of the Cu horizon there was often 2–3 cm of very lithic-rich lapilli, and this was discarded before combining the cores for analyses. Consequently, for the Atiamuri and Wairakei study sites, the sum of the depths of the soil horizons was slightly less than 60 cm (Table 2).

Pits were dug at 25 m along each transect. From each pit, bulk density samples were taken using cores 6 cm in diameter and 5 cm deep. In each pit, three bulk density cores were taken per soil horizon, covering the total depth of the horizon.

Total C and N

Soil samples from the tube corer were air-dried and sieved through a 2-mm sieve in order to obtain the fine-earth fraction. During sieving, any visible charcoal and woody material was removed by hand and discarded. Any of the constituents of the soil (pumice, wood fragments, green plant material) that would not pass through the 2-mm sieve were discarded. Sieved and dried samples were subsampled using a riffle to split the sample in half until ~10 g of sample remained. The smaller fine-earth subsample was crushed to a fine powder using an agate mortar and pestle, and air-dry samples were analysed for total C and N by high temperature combustion using a LECO furnace (LECO Corp., St. Joseph, MI, USA) (Blakemore *et al.* 1987). New Zealand soils contain little carbonate and total C provides a good measure of soil organic C (Metson *et al.* 1979).

The moisture factor of the air-dry fine-earth samples was calculated after oven drying at 105°C for 24 h and reweighed after cooling in a desiccator. The moisture factor was calculated (McLaren and Cameron 1996) and used to convert the air-dry data to an oven-dry basis.

Bulk density and fine earth fraction

Soil bulk density cores were dried intact at 105°C for 24 h. Dry bulk density was calculated from the mass of oven-dry soil and the volume of the bulk density core.

Only the fine-earth fraction of the soil was analysed for C and N, so in order to estimate the amount of C or N in the whole profile, the density (g cm^{-3}) of the fine-earth proportion of the

Table 2. Average horizon depth (cm) across all treatments and proportion (%, by weight) of C and N in each horizon for Atiamuri, Tokoroa and Wairakei study sites on Taupo Pumice Soil

Study site	Horizon	Depth (cm)	C	N
Atiamuri	Ap	0–14.0	73.6	59.4
	Bw	14.0–27.7	17.5	20.4
	Cu	27.7–57.8	8.9	20.2
Tokoroa	Ap	0–11.9	59.8	57.2
	Bw	11.9–25.6	26.2	23.0
	Cu	25.6–50.3	14.0	19.8
Wairakei	Ap	0–15.7	76.7	64.4
	Bw	15.7–36.1	17.6	22.5
	Cu	36.1–58.6	5.7	13.2

soil profile (ρ_{fef}) was calculated. The intact core samples were used for this after the whole-soil dry bulk density measures had been completed. Soil from the core was sieved through a 2-mm sieve, oven-dried and weighed, and the density (ρ_{fef}) of the fine-earth fraction was calculated from the mass (g) of fine-earth fraction divided by the total volume (cm^3) of the bulk density core.

Carbon mass (kg m^{-2}) in each horizon was calculated using the relationship:

$$M_C = \left[\frac{(T_h \times P_C \times \rho_{fef})}{10}\right] \times MF$$

where M_C is C mass in an average horizon (kg m^{-2}), T_h is horizon thickness (cm), P_C is C percentage (%) of the fine-earth fraction; ρ_{fef} is dry bulk density of the fine-earth fraction (g cm^{-3}), MF is moisture factor determined for the ground C and N samples after oven drying at 105°C, and 10 is a factor to convert to kg m^{-2}. Nitrogen in the soil profile was calculated in a similar manner.

Statistical analyses

Regression analyses of total C and N concentrations after conversion to pasture were undertaken on the Ap, Bw, Cu and combined horizons after a logarithmic transformation [log10(number of years since conversion + 1)] to normalise the time data. To include the forest profiles before conversion (where $t = 0$) all data were transformed using this formula. At sites where all three profiles were from a single paddock, samples were considered pseudo-replicates, and so after separate chemical and physical analysis, these were averaged and treated as a single sample for statistical testing. There were no 'paddocks' in the mature forest sites, and therefore data from the three transects at each site were averaged. The number of replicates for the various times since conversion varies from 1 to 3 (Table 1). Regression analyses were completed using Statistica V8 (StatSoft Inc. 2002).

Results

Total C and N in the soil profile

Horizon thicknesses were similar for the three soils with the Cu horizons being the greatest (22.5–30.1 cm) thickness (Table 2). By far the greatest proportion of total C was in the Ap horizons (59.8–76.7%) with only a small proportion (5.7–14%) being in the Cu horizon. The greatest proportions of total N were also in the Ap horizons (57.2–64.4%), but there was still a substantial proportion (13.2–20.2%) in the Cu horizons (Table 2) Overall, the Tokoroa profile contained more total C than did the Atiamuri or Wairakei, across all three treatments (pine, converted, long-term) (Table 3). For all soils, the *P. radiata* profiles always contained much less C and N than the long-term pastures (Table 3). The greater mass of total C and N in the Tokoroa profile was due to the higher concentrations in the Bw and Cu horizons (Table 4).

Changes in total mass of C and N after conversion

In general, the amount of total C and N in the soil profiles increased the longer the soils had been under pasture, but the data showed considerable variability (Fig. 1). Total C and total N data were regressed against the logarithm of the number of years since conversion from pine forest to pasture (Table 4).

Table 3. Comparison of total C and N contents (kg m^{-2}) of soil profiles (sampled to 60 cm) at Atiamuri, Tokoroa and Wairakei, from second- or third-rotation radiata pine before conversion to dairy pasture, total C and N at 2–11 years after conversion, and contents of long-term dairy and sheep–beef pastures (40–80 years)

l.s.d., Least significant difference, two-tailed test at $P = 0.05$

Site	Land use	Years since conversion	Total C	Total N
Atiamuri	Pine	–	5.60	0.534
Tokoroa	Pine	–	9.32	0.612
Wairakei	Pine	–	4.75	0.362
Combined: Mean and l.s.d. ($n = 3$)			6.55 ± 6.61	0.503 ± 0.348
Atiamuri	Pasture	2	6.38	0.606
Atiamuri	Pasture	5	5.83	0.595
Atiamuri	Pasture	11	6.10	0.601
Tokoroa	Pasture	2	10.13	0.596
Tokoroa	Pasture	3	8.39	0.604
Tokoroa	Pasture	5	8.32	0.548
Wairakei	Pasture	2.5	8.07	0.542
Wairakei	Pasture	3	6.66	0.476
Wairakei	Pasture	4	8.61	0.633
Wairakei	Pasture	4.5	11.42	0.735
Combined: Mean and l.s.d. ($n = 10$)			7.99 ± 1.835	0.594 ± 0.068
Atiamuri	Dairy pasture	80	9.10	1.039
Tokoroa	Dairy pasture	40	10.03	0.866
Tokoroa	Sheep and beef pasture	50	11.75	1.052
Wairakei	Dairy pasture	60	9.14	0.967
Wairakei	Dairy pasture	40	10.26	1.025
Combined: Mean l.s.d. ($n = 5$)			10.06 ± 1.70	0.990 ± 0.119

At the Tokoroa site, there were no significant changes in total C masses in any of the soil horizons or the combined profile, as shown by non-significant slope factors (no significant increase or decrease). For the Atiamuri site, there were significant increases in total C mass of the Ap horizon ($P < 0.001$) and the combined profile ($P < 0.01$). At the Wairakei site, there were significant ($P < 0.05$) increases in total C masses with increasing age of pasture in the Ap, Bw and combined soil profile (Table 4).

Changes in the mass of total N at the three study sites showed similar patterns to those of total C, but with slightly higher significance. There were significant ($P < 0.001$) increases in the mass of total N in the Ap horizon and combined profile at the Atiamuri site. There were significant increases in N mass of the Ap ($P < 0.01$) and combined profile ($P < 0.05$) at Tokoroa, and in the Ap, Bw and combined profile ($P < 0.001$) at the Wairakei site.

In general, even when not significant, the rates of change in total C and N in the Ap horizons were much greater than those in the Bw and Cu horizons and similar to those in the combined profile, suggesting that most of the changes in the combined profile were driven by those of the Ap horizon. The rates of increase of both C and N declined markedly through time, being almost 6-fold less at 10–50 years compared with 0–10 years. For example, averaged over the 0–10-year period after conversion,

Table 4. Regression of total C and total N (kg m^{-2}) in the Ap, Bw and Cu horizons of Atiamuri, Tokoroa and Wairakei study sites on Taupo Pumice Soil plotted against logarithm of the number of years ($\log_{10}$years + 1) since conversion from plantation forestry to pasture including original long-term forest and pastures sites

Soils were sampled to a total depth of 60 cm. Mean total C and N is the grand mean of all times since conversion. Values in parentheses for the slope and intercept columns are standard errors. *$P < 0.05$; **$P < 0.01$; ***$P < 0.001$

Sequence	Horizon	Grand mean total C and N	Slope	Intercept	Adjusted R^2
		Total C			
Atiamuri	Ap	5.34	1.97 (0.45)**	3.3 (0.4)***	0.78***
	Bw	1.67	0.03 (0.17)	1.1 (0.2)***	<0.0001
	Cu	0.69	0.00 (0.04)	0.6 (0.05)***	<0.0001
	Combined	7.20	2.0 (0.45)**	5.02 (0.54)***	0.65**
Tokoroa	Ap	5.40	0.86 (0.49)	5.01 (0.6)***	<0.0001
	Bw	2.49	0.11 (0.32)	2.37 (0.4)***	<0.0001
	Cu	1.35	0.01 (0.06)	1.34 (0.08)***	<0.0001
	Combined	9.25	0.89 (0.69)	8.75 (0.84)***	0.09
Wairakei	Ap	6.13	1.55 (0.60)*	5.07 (0.67)***	0.26*
	Bw	1.47	0.49 (0.20)*	1.00 (0.22)***	0.25*
	Cu	0.46	–0.01 (0.06)	0.55 (0.06)***	0.13
	Combined	8.05	1.92 (0.72)*	6.62 (0.81)***	0.27*
		Total N			
Atiamuri	Ap	0.409	0.29 (0.04)***	0.20 (0.04)***	0.87***
	Bw	0.140	0.00 (0.02)	0.19 (0.03)***	<0.0001
	Cu	0.139	0.00 (0.02)	0.24 (0.02)***	<0.0001
	Combined	0.689	0.30 (0.06)***	0.63 (0.07)***	0.74***
Tokoroa	Ap	0.408	0.19 (0.05)**	0.25 (0.06)**	0.74**
	Bw	0.164	0.01(0.03)	0.20 (0.03)***	<0.0001
	Cu	0.141	–0.01 (0.03)	0.24 (0.03)***	<0.0001
	Combined	0.713	0.23 (0.08)*	0.69 (0.09)***	0.54*
Wairakei	Ap	0.436	0.32 (0.04)***	0.20 (0.04)***	0.84***
	Bw	0.152	0.13 (0.03)***	0.10 (0.03)**	0.55***
	Cu	0.089	–0.10 (0.06)	0.55 (0.06)***	0.13
	Combined	0.677	0.39 (0.06)***	0.52 (0.07)***	0.73***

the mean rate of increase in total C at the Atiamuri site was 0.208 kg C m^{-2} year^{-1}, and averaged over 10–50 years was 0.033 kg C m^{-2} year^{-1}. Equivalent values for total N at the Atiamuri site were 0.031 and 0.005 kg N m^{-2} year^{-1}, respectively. The Wairakei site showed similar trends, with total C accumulating at averages of 0.200 and 0.032 kg C m^{-2} year^{-1} at 0–10 years and 10–50 years, respectively, and total N accumulating at averages of 0.041 and 0.007 kg N m^{-2} year^{-1} at 0–10 years and 10–50 years, respectively. The total C regressions for the Tokoroa chronosequence were non-significant and no rate of change could be calculated (Table 3). The amounts of total C and N in the soil profile from long-term pastures (40–80 years) were similar for all three study areas, reaching 9.1–10.2 kg C m^{-2} and 1.02–1.25 kg N m^{-2} (to 60 cm depth).

Discussion

Total C and N in the soil profile

Our New Zealand data appear consistent with international data for forest-to-pasture conversions in temperate zones, where, overall, there was no net change in C contents, or significant increases in soil C, particularly when this was combined with the introduction of improved pasture species, fertilisers and a lenient grazing regime (see reviews by Conant *et al*. 2001; Murty *et al*. 2002). New Zealand studies on forest and pasture comparisons on other Soil Orders have also reported greater total C under pastures than under forest or scrub, but those studies generally sampled to much shallower soil depths (Walker *et al*. 1959; Giddens *et al*. 1997; Hedley *et al*. 2009; Schipper and Sparling 2011; Hewitt *et al*. 2012) than used in the current study. There is often greater variability in total C contents of lower soil horizons (Franzluebbers 2009; Kravchenko and Robertson 2011), which can mask changes in the total soil profile, even when changes in the A horizon may be significant (Kravchenko and Robertson 2011; Schipper and Sparling 2011). Our current data differ from the pattern reported by Schipper and Sparling (2011) in that changes in total C and N at the Atiamuri and Warakei study areas were still detectable and significant even with the inclusion of the Bw and Cu horizons down to 60 cm. No change in total C was detected at the Tokoroa study site, but this site had a greater starting total C content than Atiamuri and Wairakei, largely because of greater C contents in the Bw and Cu horizons. This greater starting C content, plus the variability in the data, led to the slope of the regression for total C being shallow and non-significant at this site.

The final amounts of total C accumulated under long-term pasture (40–80 years) were very similar (9.1–10.2 kg C m^{-1}) at

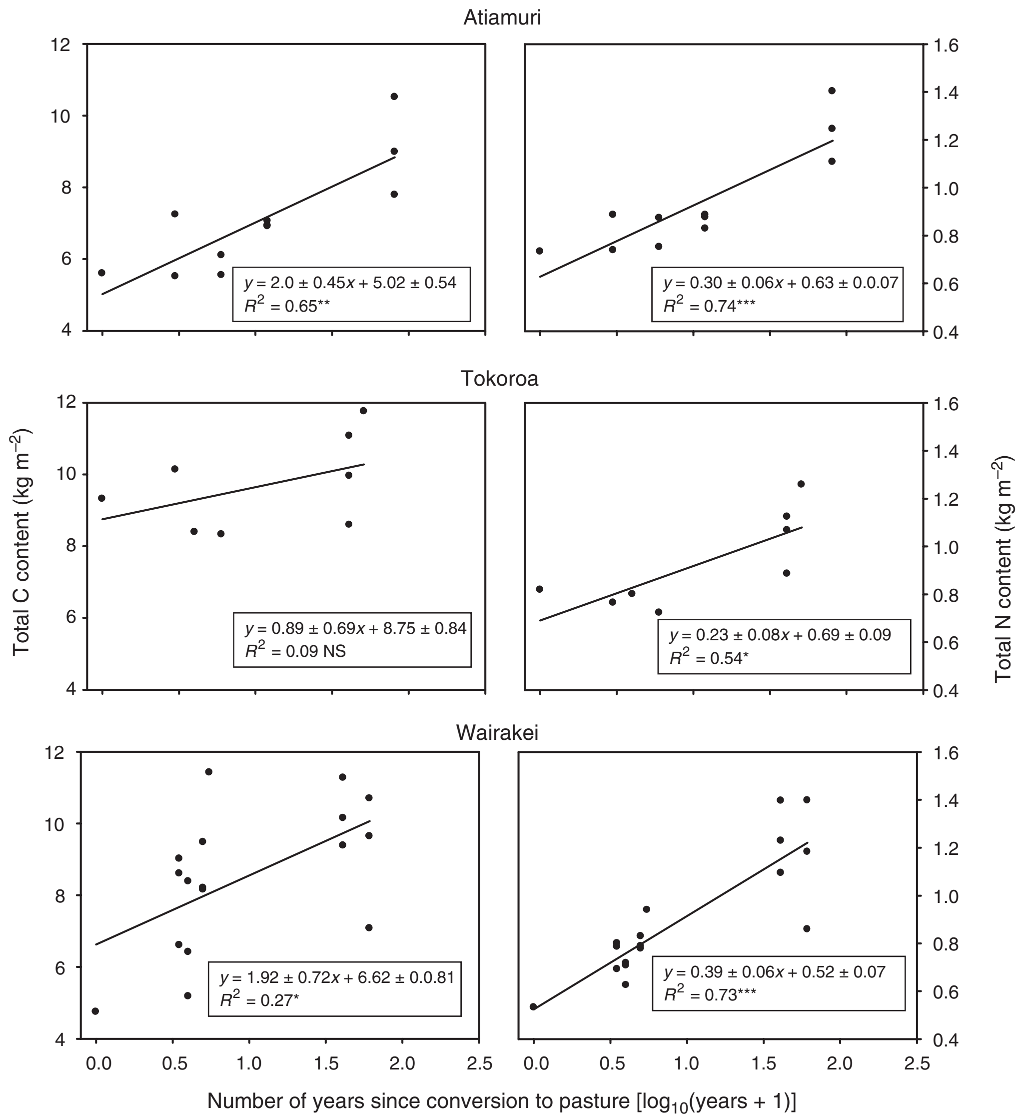

Fig. 1. Semi-log plot of total C and N contents (kg m^{-2}) in the soil profile (0–60 cm) of Taupo Pumice Soil in a chronosequence of study sites at Atiamuri, Tokoroa and Wairakei after conversion from radiata pine plantation to dairy pasture. Slope, intercept, standard error and R^2 (adjusted) are presented. NS, Not significant; *$P < 0.05$; **$P < 0.01$; ***$P < 0.001$.

all three sites, despite the different starting values (4.7–9.3 kg C m^{-1}) immediately before conversion. The final amounts (to 60 cm depth) are reasonably close to the soil carbon stock reported by Tate *et al*. (1997) for pumice soils of 8.3 kg C m^{-1} to 0.25 m and 13.2 kg C m^{-1} to 1 m depth. Our data are similar to those of Hewitt *et al*. (2012), who reported that a Taupo Pumice Soil contained 3.27 and 6.69 kg C m^{-1}, respectively, for matched, mature (pre-1990) forest and pasture sites sampled to 30 cm depth. That represents an increase of 3.42 kg C m^{-1} following a change from forest to pasture, similar to that found here for the Atiamuri (3.5 kg C m^{-1}) and Wairakei (4.36 kg C m^{-1}) sites, but very much greater than the Tokoroa site, which showed no significant change in C contents.

Giddens *et al*. (1997) also reported no significant differences in the total C content of soils under established pine plantations and improved pastures on a range of New Zealand Brown Soils, but noted that the total N content was significantly greater under pastures. In our study, increases in the total N contents following pasture establishment were significant at all three of our sites. In our study, the N status of the soils will have been increased by the amounts of N fertiliser of ~200 kg N ha^{-1} applied to the pasture soils each year (Lewis 2011). However, this fertiliser addition was not sufficient to explain the increases in total N in the soil profile. These increases, over the first 10 years after conversion, were 0.032, 0.024 and 0.041 kg N m^{-1} $year^{-1}$ for the Atiamuri, Tokoroa and Wairakei sites, respectively. This implies considerable additional N input of ~0.02 kg N m^{-1} from white clover, which remained abundant in the swards despite the fertiliser additions. Ledgard *et al*. (2001) reported annual N fixation rates of up to 0.0212 kg N m^{-1} in grazed dairy pastures in New Zealand, although this was reduced to nearer 0.01 kg N m^{-1} when 0.02 kg N m^{-1} fertiliser N was also applied. Further contributions from animal feed supplements are also possible.

Rates of C and N accumulation

The rate of C and N accumulation after conversion was greatest in the first 5 years after conversion, with the rate of accumulation at 1–10 years being ~6 times that at 10–50 years. This is again consistent with published reports; Tate *et al*. (1997, 2005) noted rapid accumulation of soil C after conversion from native vegetation to pastures and that a new steady-state was reached after 20 years, after which C changes only slowly. However, the rates of accumulation in our study were slower than some previously reported. Hedley *et al*. (2009) suggested that overall accumulation of total C on Taupo Pumice Soils for the first 5 years after conversion was equivalent to 0.61 kg C m^{-2} $year^{-1}$. In our study, accumulation rates of soil C in the whole profile over the first 10 years after conversion were 0.2 kg C m^{-1} $year^{-1}$ at Wairakei and 0.21 kg C m^{-1} $year^{-1}$ at Atiamuri, with no significant change at Tokoroa. These rates over 0–10 years for our study were at most one-third of those reported by Hedley *et al*. (2009) for 1–5 year periods also on Taupo Pumice Soil. Our approach differed from that of Hedley *et al*. (2009) in that we had a longer chronosequence after forest conversion, sampled soil to greater depth, and fitted a regression curve to the data to estimate the rates of change. Our estimates for total C accumulation are nearer to the reports by Walker *et al*. (1959), who noted an initial accumulation of 0.125 kg C m^{-1} $year^{-1}$ averaged over the first 25 years after conversion of New Zealand indigenous forest to pasture, and the findings of Schipper and Sparling (2011), who estimated that the average rate of C accumulation of 10 pasture chronosequences on a range of soils was ~0.1 kg C m^{-1} $year^{-1}$ over the first 5 years after recolonising native scrub vegetation. Similar patterns of increasing soil C reaching a stable level some 20 years after establishment of grasslands are commonly reported (Walker *et al*. 1959; Metherell 2003; Tate *et al*. 2005; Schipper and Sparling 2011).

The absence of a significant slope factor for the Cu horizon when regressing total C against time since conversion (Table 3) suggests that this horizon did not contribute to the change in total C of the whole profile. The total combined depth of the Ap and Bw horizons, which did show significant slope, was ~25–35 cm. This finding adds weight to the suggestion by Hedley *et al*. (2009) that soil samples should be taken to 30 cm depth to compare changes in total C under forest and pastures. Hewitt *et al*. (2012) noted no significant changes in C contents in the 20–30 cm depth of a range of paired pasture and forest comparisons, and concluded that sampling to 30 cm depth would capture changes in total C in the soil profile. We sampled to 60 cm, but the Cu horizons showed no significant changes in total C, and we concur that sampling the soil profile to 30 cm depth will usually be sufficient to detect changes in total C after a change in land use.

Hedley *et al*. (2009) reported that annual accumulation rates of total N were equivalent to 0.045 kg N m^{-1} $year^{-1}$ at 1–5 years after conversion to pasture. Our values for the accumulation of total N in the pasture sites 0–10 years after conversion were 0.024, 0.031 and 0.041 kg N m^{-1} $year^{-1}$, respectively, for the Tokoroa, Atiamuri and Wairakei sites, much less than the rates reported by Hedley *et al*. (2009). As outlined above, our different approach and method of calculation, plus the longer chronosequence, may explain this difference. The total N content in our study sites increased proportionally much more rapidly than C content following conversion to pasture. Further work is required to identify the sources of this substantial increase in stored N, particularly for the Wairakei site, but as stated above, it is too large to be attributed solely to fertiliser inputs.

Conclusion

Conversion of radiata pine plantation to dairy pasture on this Taupo Pumice Soil has not resulted in any loss of total C down to 60 cm depth at the three sites studied, and at two of the sites has resulted in an increase in soil C. This has occurred mainly in the Ap horizons, with the increase being most rapid during the first 10 years after conversion. The management changes to stimulate pasture production has resulted in a substantial increase in the total N content of the soil profile at all three study areas.

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