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Soil C and N sequestration and fertility development under land recently converted from plantation forest to pastoral farming

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Abstract Soil organic matter accumulation and concomitant fertility changes in soils recently converted from plantation forest to pastoral agriculture in the Taupo-Rotorua Volcanic Zone have been observed, with a probable soil C sequestration rate of 6.1 t ha^{-1} $year^{-1}$, and a soil N sequestration rate of 0.45 t ha^{-1} $year^{1}$, to 150 mm soil depth, for the first 5 years after conversion at two of three selected farms. Rapid increases in Olsen P were observed, with soils reaching their optimum agronomic range within 3–5 years after conversion, at two of three farms. A decreasing C:N ratio with time since conversion reflects improved fertility status, and implies that in initial years of pasture establishment, N losses are reduced due to its immobilisation into soil organic matter. These research findings suggest that land-use change from plantation forest to pastoral farm, with inputs of N, P, K and S to soils, allows significant soil C and N sequestration for at least 5 years after conversion. This rate of C sequestration could be used as an offset for forest C sink loss in future emissions trading systems. Further research is required to at least 0.3 m depth to confirm this preliminary study.

Keywords C:N ratio; Olsen P; pH; volcanic soils

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INTRODUCTION

Plantation forest covers 7% (1.7 M ha) of New Zealand, 91% being *Pinus radiata* D. Don, and the Kaingaroa Forest, on the volcanic soils of the Central Plateau, North Island, is one of the largest planted forests in the world. Here *Pinus radiata* growth rates (for 25-year-old trees) vary between 22 and 39 m^3 ha^{-1} $year^{-1}$ (Kimberley et al. 2005), and are therefore some of the highest growth rates globally (Carle et al. 2002). This outstanding production performance is largely attributed to a deep rooting system (up to 5 m) in these volcanic soils, plus a suitable climate (Molloy 1998). Despite this success, recent economic trends have favoured deforestation of plantation forests and conversion to pastoral farming. In the Taupo-Rotorua area, 18% of the forest harvested in 2005 has been converted to mainly dairy pasture, with a proposed conversion area of approximately 60 000 ha (Brodnax 2007). This trend is mirrored on the Canterbury Plains where almost 1000 ha have been converted.

Projected implications of this land-use change include detrimental effects on air and water quality, due to increased nitrous oxide emissions and nitrate leaching, respectively, primarily due to dung and urine excreted by introduced grazing ruminants, and to a much lesser extent to increased use of nitrogen fertilisers (e.g., de Klein & Ledgard 2005). Also, this land-use change has impacted on New Zealand's greenhouse gas accounting because forests planted since 1990 can be included as "forest sinks", i.e., net consumers of carbon dioxide, during the first commitment period to the Kyoto Protocol, under

Article 3.3. However, this diminishing forest sink has resulted in a projected additional 14.7 million emission units (one emission unit is equivalent to one tonne of greenhouse gas emissions converted to carbon dioxide equivalents by the global warming potential) being added to New Zealand's "net position" (New Zealand Climate Change Office 2007) of a deficit of 41.2 million units over the first commitment period of the Kyoto Protocol (2008–12). The Permanent Forest Sinks Initiative, introduced to curb this land-use change trend, has slowed the rate of land conversion. However, it is likely that some deforestation will continue in New Zealand's 1.7 million ha of plantation forest, much of it on relatively productive agricultural soils, with increasing global returns from food production likely (ICF International 2008).

The New Zealand Land Use and Carbon Analysis System (LUCAS) accounts and reports rates of afforestation, reforestation and deforestation under Article 3.3 of the Kyoto Protocol during the first commitment period (CP1) from 2008−12 (New Zealand Ministry for the Environment 2009). It provides regional estimates of stored soil C in forests and soils and how these carbon stocks change with land use, and is best suited to providing national and regional averages. However, it is unlikely to capture individual farm scale changes in soil carbon (ICF International 2008).

Farm scale soil carbon auditing should use a combination of spatial probability sampling and improved measurement techniques (Minasny et al. 2006). Significant interest in the use of rapid *in situ* field collection of visual-NIR reflectance spectra for soil carbon analysis (e.g., Gomez et al. 2008) provides the opportunity for rapid field estimation of *in situ* soil carbon, and our research findings in this area are reported elsewhere (Kusumo et al. 2008).

The significant disruption of the soil profile which occurs as trees are ripped out during deforestation to be replaced by pasture, suggests that spatial variability will be significant in this study. Pasture is established in soil profiles that can be highly variable over a distance of only a few metres. Significant inputs of nitrogen and phosphorus fertilisers are required to build up soil fertility in such soils, which have been under forest for several decades (Wheadon & Adam 2006). However, case studies report that pasture establishes very rapidly in these volcanic soils, with newly converted land producing over 1100 kg milksolids ha^{-1} (Wheadon & Adam 2006).

A global review of the effects of conversion of forest land to pasture (Murty et al. 2002) reported widely different changes in soil C ranging from –51 to +164%, at 109 case study areas. Largest increases were found after conversion from native vegetation to leguminous pastures in Western Australia, attributed to low initial soil C, application of fertiliser and careful management to avoid overgrazing. Maximum soil C decreases were recorded for a 20 to 31-year-old pasture in Costa Rica, which had replaced wet tropical forest. Another global review (Guo & Gifford 2002) concluded that soil C stocks increase after land-use change from native forest to pasture (+8%), (n = 170), with precipitation and sampling depth having significant effects on the magnitude of change. Clearing of forest for pasture in areas with 2000−3000 mm precipitation sequestered significantly more soil C stocks (+24%) compared with lower rainfall areas. Also, soil C stocks increased by 7−13% if sampling depth was less than 1 m, but there was no change below 1 m, and no marked differences between topsoil and subsoil C changes within the 1 m sampling depth. Kirschbaum et al. (2008) reported lower soil C stocks after afforestation of pastoral sites to 18-year-old pine forest in Australian Capital Territory, Australia. Sites lost 5.5 t C ha^{-1} and 588 kg N ha^{-1} to 1 m sampling depth, although an additional 6.1 t C ha^{-1} and 393 kg N ha^{-1} was contributed in above-ground litter. Scott et al. (2006) conducted a similar comparison of pine forest and pasture C and N pools in the Rotorua region, New Zealand. They used the Roth-C soil C model to model C accumulation on the forest floor during the first rotation of these forest stands as 12 t C ha^{-1}, with below ground inputs of 1.53 t C ha^{-1} year^{-1} to harvest, compared with steady state pasture inputs of 9 t C ha^{-1} year^{-1} to 0.3 m soil depth. The Roth-C soil C model (Coleman & Jenkinson 1996) uses three litter quality "classes" based on the decomposition rates of organic residues of differing composition (Scott et al. 2006). Scott et al. (2006) conclude that afforestation of pastures in New Zealand leads to a decline in soil C and N cycling rates and soil temperature, and that this decline may continue for multiple rotations so that plantation forest may not necessarily be considered "C neutral" for the purpose of national carbon accounting after one rotation.

These studies highlight the fact that soil C and N equilibrium shifts, which occur with land-use changes from plantation forest to pasture, are dependent on site specific edaphic, climatic and management variables. Post & Kwon (2000) found declining soil organic carbon (SOC) levels where native forest was converted to pastures in Costa Rica, although at one site, where soil type differed, there was a significant increase in SOC. The soil at this site was a "rich volcanic soil". Another study showed that 11 out of 14 pasture conversion sites in Brazil showed soil C sequestration rates up to 740 kg C ha^{-1} year^{-1} over a 20-year period since forest clearance (Post & Kwon 2000). In New Zealand, land development of Taupo sandy silt soils in the Central Volcanic Zone in the 1950s, from native scrub to permanent pasture, increased soil C levels (0–150 mm soil depth) from 4.2 to 6.3% after 25 years (Walker et al. 1959), with half of the increase to a steady state occurring in the first 15 years (Jackman 1964). Fertiliser applications were typically 200–300 kg ha^{-1} of superphosphate at this time.

Our research, which aimed to assess the impacts of present land-use change from plantation forest to productive pastures, in the Taupo-Rotorua Volcanic Zone, on soil development in the first 5 years after conversion, is able to report some important data and trends in topsoil C and N changes.

METHODOLOGY

Site selection

Three farms on a range of soils were selected in the Taupo-Rotorua Volcanic Zone to assess soil changes and pasture development during the first 5 years after conversion of plantation forest to productive pasture. Land clearance involved tree removal with a large digger and bulldozing of organic debris into windrows at tree felling. The area between windrows was disc-cultivated, harrowed, rolled and sown with ryegrass-white clover cultivars. The windrows were then left for 2–3 years, for partial decomposition, before incorporation into the soil. The more expensive method of mulching for incorporation was not used at these sites. Mean annual rainfall is 1102–1401 mm and air temperature is 11.9–12.8°C (1971–2000 period). At each farm, a permanent pasture site was sampled as well as one or two conversion sites on comparable soil types. At each site three transects were chosen, and along each transect five positions were sampled in May 2006.

The three farms were:

Atiamuri (38°19.9′S, 176°2.7′E)
- 1-year conversion *Pinus radiata* to pasture
- 5-year conversion *Pinus radiata* to pasture
- Permanent pasture

Manawahe (37°59.8′S, 176°41.6′E)
- 1-year conversion *Eucalyptus nitens* to pasture
- 5-year conversion *Pinus radiata* to pasture
- Permanent pasture

Tokoroa (38°9.9′S, 175°47.8′E)
- 3-year conversion *Pinus radiata* to pasture
- Permanent pasture

The conversion sites had previously been forested for 23 years at Atiamuri; 26 years (*Pinus radiata*) and 10 years (*Eucalyptus nitens*) at Manawahe; and 63 years at Tokoroa. Pumice soils (Hewitt 1998) at Atiamuri are mapped as Taupo sandy silts (Vucetich & Wells 1978), consisting typically of 150 mm of topsoil over a yellow-brown raw pumice subsoil (Orthic Pumice soils; Hewitt 1998). Tephric Recent soils (Hewitt 1998) at Manawahe have formed in Kaharoa Ash, with little profile differentiation in the dark sandy raw pumice parent material. At Tokoroa, the soils are older, more weathered deep fertile ash soils, probably intergrade Allophanic soils (Hewitt 1998), with some pumice present in the profile.

During pasture seedbed preparation at the Atiamuri and Tokoroa farms, capital dressings of diammonium phosphate (DAP) were added supplying up to 137 kg ha^{-1} P, with additions of Mg, trace elements and lime. After the initial year, conversion pastures at all three properties typically receive two N dressings annually (autumn and spring) of between 74 and 88 kg N ha^{-1} year^{-1} (Table 1).

Soil and pasture sampling

Soils were sampled to 75 mm depth (five cores bulked per position, five positions per transect) for chemical analysis to assess soil fertility status; and to 150 mm depth for total carbon and nitrogen analysis, during May 2006. Intact soil cores, 100 mm diameter and 80 mm in height, were also taken from the middle of each sample depth, at each sampling position, for estimation of bulk density. Annual pasture production was assessed from data collected between October 2004 and November 2006 at 4–6 week intervals using the single trim and cut technique from small pasture exclusion cages (3 × 0.22 m^2 per site) (Hawke 2004). Annual dry matter (DM) yields are expressed per hectare.

Laboratory analysis

Soils were air-dried and sieved (2 mm) before chemical analysis. These air-dried soils were then analysed for Olsen P, P retention, pH, cation exchange capacity (CEC), total C and total N. Herbage was oven-dried at 70°C, ground and then analysed for total N. Standard laboratory analytical procedures were used (Blakemore et al. 1987; Landcare Research Environmental Chemistry Laboratory 2009).

Statistical analysis

The number of soil replicates required to confirm whether any measured difference in soil C between conversion and permanent pasture sites is significant was assessed at each site. The method outlined by Clay et al. (2007) was conducted in Microsoft Excel 2003 (©1985–2003 Microsoft Corporation), and used the formula (Eqn 1):

$$n = t^2 s^2 / D^2 \quad (1)$$

where, n is the number of soil samples required

t is the t value for probability level ($P \leq 0.05$) and degrees of freedom (d.f. = 14)

s is the standard deviation of the 15 replicate values obtained at each site

D is the desired confidence interval.

In addition, the difference between soil C values at paired sites was assessed for statistical significance using a two-tail Student's t-test in Microsoft Excel 2003 (©1985–2003 Microsoft Corporation).

Also, the variability of soil C and N analyses within and between sites was assessed by calculating the coefficient of variation (% CV).

RESULTS

Soil fertility analyses

The mean Olsen P values at the Atiamuri 1-year and 5-year conversion sites were 16 µg P ml^{-1} and 38 µg P ml^{-1} soil respectively (Fig. 1A; Table 2). At the Tokoroa farm the 3-year conversion site had an Olsen P of 18 µg P ml^{-1} soil and the permanent pasture site had an Olsen P value of 56 µg P ml^{-1}. The Manawahe 1-year, 5-year conversion and permanent pasture sites have Olsen P values of 26, 12 and 30 µg P ml^{-1} soil respectively.

The highest P retention of the Tokoroa soils (Fig. 1B; Table 2) reflects the greater allophane content of these older soils formed from andesitic tephra compared with soils at the other sites formed from pumiceous material. The soil P retention and pH (Fig. 1C; Table 2) tend to be lower, and CEC (Fig. 1D; Table 2) tends to be higher with time since conversion (Fig. 1).

Soil carbon and nitrogen

Total soil C and N increased after conversion of these soils from plantation forest to well managed pastoral soils (Fig. 2A,B; Table 2).

Mean soil C increases in the present study were 4.07 mg cm^{-3} per year in the top 150 mm of soil, for the first 5 years since conversion at the two farms where 1-year and 5-year conversion sites were available. Soil C (in the top 150 mm of soil) in the Taupo sandy silt soil at Atiamuri increased from 25.3 mg cm^{-3} in the first year after conversion to 39.6 mg cm^{-3} under permanent pasture, a significant 56% increase in soil C, and at Manawahe a 156% increase is observed. All soil N changes with time were significant ($P \leq 0.05$), whereas soil C changes were only significant ($P \leq 0.05$) between 1-year and 5-year conversion sites (Table 3), for the sampling strategy adopted in this study.

A greater number of soil samples would be required for the smaller measured changes between paired sites (1.5 mg cm^{-3} at Atiamuri, 2.3 mg cm^{-3} at Manawahe and 2.6 mg cm^{-3} at Tokoroa) to be significant (Table 3). For example, using Eqn (1)

Table 1 Typical annual fertiliser form and rate applied after land conversion from forest to pasture. DAP, Diammonium phosphate; SSP, single superphosphate; KCl, potassium chloride; SOA, ammonium sulphate.

Farm	Time	Fertiliser form	Rate	N (kg ha^{-1})	P (kg ha^{-1})	K (kg ha^{-1})	S (kg ha^{-1})	Trace
Atiamuri	Autumn	DAP	400	72	80	–	–	
	Spring	SSP:KCl:SOA mix [42:35:23]	330	16	13.4	58	32	Co, Se
Manawahe	Autumn	Sustain/Clover King/Potash	260	40	18	10	36	
	Spring	Sustain/Clover King/Potash	260	40	18	10	36	
Tokoroa	Initial (2003)	Super 10:DAP mix [83:17][a]	1200	36	137	–	2	
	Spring (2004–05)	Cropzeal 15P	300	40	45	37	2	
	Autumn (2004–05)	DAP	200	36	40			
	Spring (2005–06)	Super 10K + urea + calmag mix [85:7:8]	1150	37	76	98	82	
	Autumn (2005–06)	DAP:KCl mix [60:40]	350	37	42	70		

[a], Cultivated in first year for swedes.

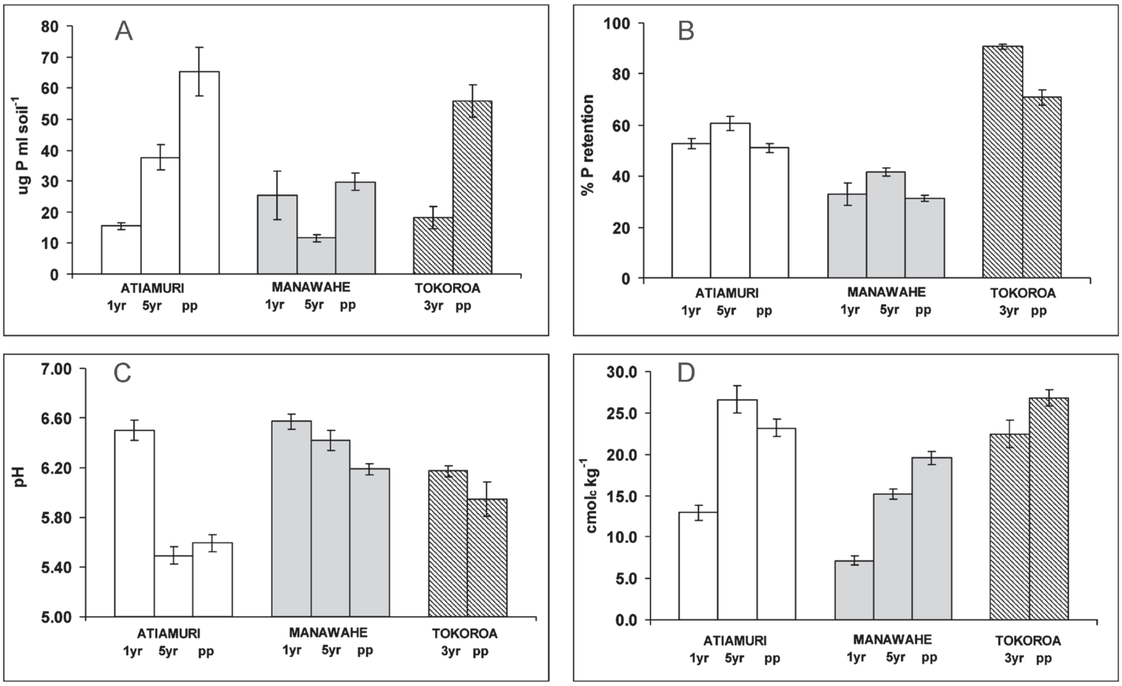

Fig. 1 **A**, Olsen P; **B**, P retention; **C**, pH; and **D**, cation exchange capacity (CEC) of 0–75 mm soil samples (mean of 15 bulked replicates) taken from permanent pasture (pp) and pastures recently converted from forest (1-year, 3-year, 5-year).

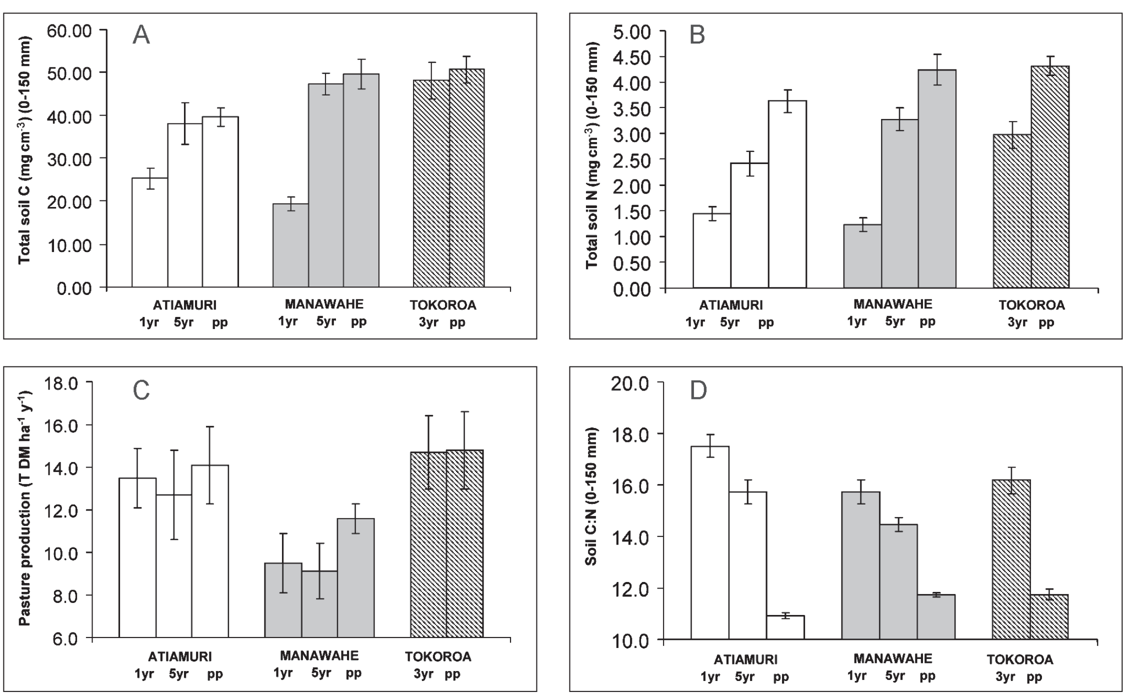

Fig. 2 **A**, Total C; **B**, total N; **C**, pasture production; and **D**, C:N ratio of 0–150 mm soil samples (mean of 15 bulked replicates) taken from permanent pasture (pp) and pastures recently converted from forest (1-year, 3-year, 5-year).

we calculate that we would need 103, 101 and 66 soil samples at Atiamuri, Manawahe and Tokoroa, respectively, for these measured changes to be significantly different ($P \leq 0.05$).

As time from conversion increased, soil N increased at 0.30 mg cm^{-3} per year for the first 5 years, (0–150 mm soil depth), at Atiamuri and Manawahe farms, with an overall narrowing of C:N ratio with time, at all three farms. The C:N ratio decreased from 17.9 and 15.7 in newly converted soils to 14.8 and 13.9 in 5-year conversion soils to 10.6 and 10.9 in permanent pastures, respectively, reflecting the proportionally greater accumulation of N compared with C in these soils, as the ryegrass-clover sward establishes with accompanying N fixation and N fertiliser inputs (Table 1). This narrowing of C:N ratio, also noted by other workers (e.g., Walker et al. 1959), reflects the process of added N to the soil being immobilised into soil organic matter, until a point where C:N ratio stabilises at about 10–11.

Integrated fertility and grazing management of these newly converted soils yields high pasture productivity in initial years after conversion, between 9.1−14.7 t DM ha^{-1} year^{-1} (Fig. 2C, Table 2). Eighty-one percent and 95% of permanent pasture yield was achieved at Manawahe and Atiamuri, respectively in the first year after conversion.

Table 2 Olsen P, pH, cation exchange capacity (CEC), P retention, pasture production, total N, total C and C:N ratio of 0–75 [0–150] mm soil samples of 15 bulked replicates from three farms where forest has recently been converted to pasture. Standard error (SE) in italic. 0–150 mm soil depth is in square brackets.

		Olsen P		pH	
Farm	Site	(µg P ml^{-1})		*SE*	*SE*
Atiamuri	1-year conversion	15.6	*1.2*	6.50	*0.08*
	5-year conversion	37.7	*4.1*	5.49	*0.07*
	Permanent pasture	65.4	*7.9*	5.59	*0.07*
Manawahe	1-year conversion	25.6	*7.9*	6.57	*0.06*
	5-year conversion	11.7	*1.2*	6.42	*0.08*
	Permanent pasture	29.9	*2.9*	6.19	*0.05*
Tokoroa	3-year conversion	18.3	*3.5*	6.17	*0.05*
	Permanent pasture	55.8	*5.3*	5.95	*0.14*

		CEC		P retention		Pasture production	
Farm	Site	(meq 100 g^{-1})	*SE*	(%)	*SE*	(t DM ha^{-1} year^{-1})	*SE*
Atiamuri	1-year conversion	12.9	*0.9*	52.7	*2.0*	13.5	*1.4*
	5-year conversion	26.6	*1.6*	60.6	*2.7*	12.7	*2.1*
	Permanent pasture	23.2	*1.1*	51.0	*1.9*	14.1	*1.8*
Manawahe	1-year conversion	7.2	*0.5*	33.0	*4.4*	9.5	*1.4*
	5-year conversion	15.2	*0.6*	41.7	*1.5*	9.1	*1.3*
	Permanent pasture	19.5	*0.8*	31.4	*1.2*	11.6	*0.7*
Tokoroa	3-year conversion	22.5	*1.7*	90.7	*1.1*	14.7	*1.7*
	Permanent pasture	26.8	*1.0*	70.9	*2.9*	14.8	*1.8*

		Total N		Total C		C:N ratio	
Farm	Site	(mg cm^{-3})	*SE*	(mg cm^{-3})	*SE*		*SE*
Atiamuri	1-year conversion	1.6 [1.5]	*0.1 [0.1]*	27.4 [25.3]	*1.7 [2.4]*	17.9 [17.6]	*0.5[0.4]*
	5-year conversion	3.6 [2.8]	*0.2 [0.3]*	54.7 [44.4]	*4.3 [5.1]*	14.8 [15.1]	*0.4[0.5]*
	Permanent pasture	5.0 [3.6]	*0.2 [0.2]*	52.8 [39.6]	*2.1 [2.2]*	10.6 [10.9]	*0.1[0.1]*
Manawahe	1-year conversion	0.9 [0.8]	*0.1 [0.1]*	13.0 [12.1]	*1.1 [1.7]*	15.7 [16.2]	*0.4[0.4]*
	5-year conversion	3.9 [3.3]	*0.2[0.2]*	53.6 [47.3]	*2.6 [2.5]*	13.9 [14.7]	*0.3[0.3]*
	Permanent pasture	6.6 [4.2]	*0.6 [0.3]*	72.0 [49.6]	*6.8 [3.3]*	10.9 [11.7]	*0.1[0.1]*
Tokoroa	3-year conversion	3.4 [3.0]	*0.3 [0.3]*	52.1 [48.1]	*4.0 [4.1]*	15.2 [16.1]	*0.5[0.5]*
	Permanent pasture	5.6 [4.3]	*0.2 [0.2]*	62.1 [50.7]	*2.7 [2.9]*	11.1 [11.7]	*0.2[0.2]*

Table 3 Calculated differences (Δ) in soil C and N (0–150 mm soil depth) between paired sites at each farm. ***, Highly significant ($P \leq 0.005$); *, borderline significant ($P \leq 0.05$); NS, not significant ($P \geq 0.05$).

Farm	(Site 1)—(Site 2)	Δ C (mg cm^{-3})		Δ N (mg cm^{-3})	
Atiamuri	(5-year conversion)—(1-year conversion)	12.8	*	1.0	***
	(Permanent pasture)—(5-year conversion)	1.5	NS	1.2	***
Manawahe	(5-year conversion)—(1-year conversion)	27.9	***	2.0	***
	(Permanent pasture)—(5-year conversion)	2.3	NS	1.0	*
Tokoroa	(Permanent pasture)—(3-year conversion)	2.6	NS	1.3	***

Table 4 Coefficient of variation (% CV) of soil C and N analyses ($n = 15$) for each site selected at the three farms where plantation forest has been cleared for productive pastoral farming (0–150 mm soil depth).

Farm	Site	Site C (% CV)	Site N (% CV)
Atiamuri	1-year conversion	37	37
	5-year conversion	49	38
	Permanent pasture	22	23
Manawahe	1-year conversion	33	40
	5-year conversion	21	26
	Permanent pasture	26	27
Tokoroa	3-year conversion	35	34
	Permanent pasture	24	16

Site CV was ≤27% for all soil C and N analyses on permanent pasture, and >33% for <3-year conversion sites (Table 4). The largest CV of 49% was observed at the Atiamuri 5-year conversion site, which is probably due to sampling across a zone of windrow incorporation. The significant spatial variability of soil C and N implied by these CV values (compare CVs of 9% quoted by Schipper & Sparling (2000) for a national survey) exemplifies the need for higher resolution sampling for soil C and N analysis to more accurately assess soil C and N changes with time (Minasny et al. 2006; Kusumo et al. 2008).

DISCUSSION

Olsen P status, soil C and N concentrations have been used as indicators of the stage of fertility development of pasture soils (Nguyen & Goh 1990; Morton & Roberts 1999; Lambert et al. 2000). Regular fertiliser inputs at all sites tended to increase Olsen P status. However, the range in Olsen P values reflects interactions between different fertiliser application rates, soil P retention, and P removals and transfers due to the farming system. The Tokoroa soils received much higher rates of P (Table 1) but also had higher percentage P retention values (Fig. 1B; Table 2) which tended to reduce the increase in Olsen P per kg P applied per hectare. The Manawahe 1-year and 5-year conversions and permanent pasture sites had Olsen P values of 26, 12 and 30 μg P ml^{-1} soil respectively. The higher Olsen P of the Manawahe 1-year compared with the 5-year conversion site reflects the recent autumn fertiliser application that had been applied (Table 1). In another study on the effects of fertiliser treatments on grazed pastoral hill country soils, similar variable changes in Olsen P values have been reported (Lambert et al. 2000). These workers showed that Olsen P continually increased with high rates of superphosphate application (625 kg ha^{-1} year^{-1} for 5 years, then 375 kg ha^{-1} year^{-1} superphosphate fertiliser applied), but reached a plateau after 10 years with lower superphosphate application rates (125 kg ha^{-1} year^{-1} superphosphate applied).

It is likely that the decreases in P retention noted reflect accumulation of organic matter due to pasture root establishment, plant litter and frequent dung and urine deposition by grazing ruminants in these newly established pastoral soils. Decreasing soil pH with time reflects the soil acidification process of proton release by roots during cycling of C, N and S typical of legume-based pastures (Hedley et al. 1982).

The different trends observed for accumulation of soil C and soil N are probably due to different stabilisation processes (Nguyen & Goh 1990). Therefore soil C and N may reach equilibrium after different periods of time after this land-use change. Agricultural soils have an equilibrium soil organic carbon content for a given land use and management regime, the time required to change from one equilibrium to another often being in the range of 10–100 years, or even longer (Royal Society 2001). Nguyen & Goh (1990) reported increases in soil organic carbon (SOC) for 15–16 years, and soil nitrogen for 21–26 years when up to 376 kg ha^{-1} $year^{-1}$ superphosphate was applied to pastoral soils. Metherell (2003) noted, at Winchmore, New Zealand, that soil C increased dramatically after initial development (and fertiliser inputs), but after 50 years there were no further soil C increases with fertiliser input. In fact, he noted a gradual decline in soil C at one hill country site (Ballantrae), which he suggested may be due to an increase in stocking rate and pasture utilisation as pasture development proceeded. Lambert et al. (2000) and Schipper et al. (2007) also suggest that, with time, intensification of grazing management may lead to soil C losses in permanent pastoral soils. Schipper et al. (2007) re-sampled permanent pasture soils (probably converted to pasture between 1840 and 1880) for soil C and soil N, sampled 17–30 years previously, and inferred significant soil C and N losses over this time (1060 kg C ha^{-1} $year^{-1}$, 91 kg N ha^{-1} $year^{-1}$).

The soil C increases of 156% observed at Manawahe are not as high as the highest increases of 162–164% observed by Murty et al. (2002).

Beets et al. (2002) and Pinno & Bélanger (2008) discuss the importance of comparing whole soil profiles when investigating forest to pasture land-use change effects on soil C pools, because the deeper rooting systems of forest soils will allocate soil C to greater depths than the shallower rooting system of pasture soils. Beets et al. (2002) found that surface mineral soil C (0–100 mm) is approximately 4 t C ha^{-1} higher under pasture than pine forest in their New Zealand soils, but discuss reasons to compare soils to greater depths not only because of soil C allocation to different depths under the two contrasting land uses, but also because of considerable redistribution of soil C during forest harvesting operations, with soil disturbance extending beyond the 0.30 m depth suggested by the Intergovernmental Panel on Climate Change (IPCC) for C accounting purposes (New Zealand Ministry of Agriculture & Forestry 2009). Our sampling depth to 150 mm captures the zone where rapid accumulation of grass roots occurs after clover/grass seeding, and provides a valuable comparison with other studies where soils were sampled to a similar depth (e.g., Walker et al. (1959) (0–8 inches, 0–200 mm); Schipper & Sparling (2000) (0–100 mm); Nguyen & Goh (1990) (0–75 mm); Scott et al. (2006) (0–200 mm)). Our study does not capture any differences at greater depths due to disruption of soil profiles when trees are uprooted, which can invert subsoils above topsoils in localised zones.

Analysis of observed soil N changes, in our present study, using an N balance approach, indicates that N fixation rates for these soils are approximately 340 kg N ha^{-1} $year^{-1}$, with about 80 kg N ha^{-1} $year^{-1}$ applied in fertiliser. Ledgard & Steele (1992) report that N fixed in legume/grass pastures throughout the world range from 13 to 682 kg N ha^{-1} $year^{-1}$, with the corresponding range for grazed pastures (assessed for white clover pastures only) as 55–296 kg N ha^{-1} $year^{-1}$. Jorgensen & Ledgard (1997) comment that many of these quoted values for white clover are underestimates because researchers frequently only account for N fixed by leaves ignoring the significant contribution of N fixation by roots. They suggest a correction factor of 1.7 should be used to account for N in the tissue below the cutting height when N fixation in white clover is estimated by harvesting the leaves only. This would increase the value of 296 kg N ha^{-1} $year^{-1}$ to 503 kg N ha^{-1} $year^{-1}$. We noted there was a very high proportion of clover (>50%) established in these new ryegrass-clover swards which would help to explain high N fixation levels.

These trends suggest total C is accumulating at a rate of approximately 6.11 t C ha^{-1} $year^{-1}$, and total N is accumulating at a rate of approximately 0.45 t N ha^{-1} $year^{-1}$, in the Atiamuri and Manawahe soils for the first 5 years after conversion (0–150 mm soil layer).

If we assume that the equivalent of half of the pasture production is contributed as below ground organic matter of which 58% is C, as discussed by Walker et al. (1959), then the pasture root mass alone accounts for 4.2 t C ha^{-1} $year^{-1}$. Other initial C inputs probably include incorporated tree debris, which was observed during soil sampling. Evidence of windrow incorporation into the Atiamuri 5-year conversion sites was noted, where soil C levels varied between 9.45 and 76.0 mg cm^{-3}.

This research and that reported by others (e.g., Walker et al. 1959; Jackman 1964; Nguyen & Goh 1990) indicates that improving the fertility status of high productivity New Zealand pastoral soils significantly increases soil C in surface horizons over the initial decades after land-use change. However, more recent research has shown that this increase slows to an equilibrium at approximately 50 years (Metherell 2003), and soil C increases may be reversed with sustained intensification of grazing management (Lambert et al. 2000; Metherell 2003; Schipper et al. 2007).

The capital dressings of P applied in the first 2 years after conversion resulted in optimum or near optimum Olsen P test values for pasture establishment, within the first 5 years at the Atiamuri (38 µg P ml^{-1} after 5 years) and Tokoroa farms (18 µg P ml^{-1} after 3 years) (Fig. 1A). These Allophanic soils at Tokoroa require a lower optimum Olsen P range (20–30 µg P ml^{-1}) than pumiceous soils (35–45 µg P ml^{-1}) (Morton & Roberts 1999). At the Manawahe site, where pumiceous soils occur, Olsen P values remain sub-optimal even in the permanent pasture site, presumably due to lower inputs of fertiliser.

We assume the marked increases in soil P status are largely responsible for improved pasture yields, improved N fixation (as discussed by Nguyen & Goh 1990), and therefore a greater return of plant litter and dung to soil resulting in increases in soil C.

Significant apparent levels of soil N and soil C sequestration have been observed in these soils. Soil C sequestration in the initial years after conversion partially offsets the forest sink capacity which has been lost. Reported growth rates of *Pinus radiata* in this region are between 22 and 39 m^3 ha^{-1} $year^{-1}$ (Kimberley et al. 2005). Assuming 25% fresh weight is C, these forests would then accumulate between 5.2 and 9.7 t C ha^{-1} $year^{-1}$, so the recorded soil C sequestration rate of 6.1 t C ha^{-1} $year^{-1}$ (to 150 mm) is a significant offset, which could be included in C accounting systems which assess forest biomass and soil C changes. A more complete life cycle assessment would also include the indirect C costs of, for example, added fertiliser, methane emissions from grazing ruminant animals, and nitrous oxide emissions from higher soil N levels.

The ability of these newly converted soils to sequester N suggests a large proportion of the N fertiliser applications (between 76 and 88 kg N ha^{-1} $year^{-1}$) and biologically fixed N is being immobilised into soil organic matter. This suggests that N leaching losses are slow, in initial years, which warrants further investigation.

Further research is required to confirm these initial trends, with sampling to at least 0.3 m soil depth, for the soil changes under investigation. In addition, an assessment of soil spatial variability, as described by Minasny et al. (2006), should ideally be included in any further sampling surveys.

CONCLUSIONS

At all sites in this study where plantation forestry had been converted to clover based pasture, applications of phosphatic and nitrogen fertiliser were associated with increasing topsoil phosphate status and differential increases in topsoil soil C and N contents causing decreases in the C:N ratio of the topsoil organic matter with time since conversion.

Changes in soil organic matter content caused by conversion were highly variable, reflecting soil disturbance during conversion but also reflecting differences in soil physical conditions and pasture vigour.

Significant soil C sequestration rates could be included as an offset in any C accounting of this land-use change.

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REFERENCES

Beets PN, Oliver GR, Clinton PW 2002. Soil carbon in podocarp/hardwood forest, and effects of conversion to pasture and exotic pine forest. Environmental Pollution 116: S63−S73.

Blakemore LC, Searle PL, Daly BK 1987. Methods for chemical analysis of soils. New Zealand Soil Bureau Scientific Report 80. Wellington. 103 p.

Brodnax R 2007. The next chapter in regional policy development to manage adverse effects of land use intensification. Proceedings of the FLRC Workshop Designing Sustainable Farms: Critical Aspects of Soil and Water Management. In: Currie LD, Yates L ed. Occasional Report No. 20. Fertilizer and Lime Research Centre, Massey University, Palmerston North, New Zealand. 8–9 February 2007. P. 4.

Carle JP, Vuorinen P, Del Lungo A 2002. Status and trends in global forest plantation development. Forest Products Journal 52(7/8): 12–23.

Clay DE, Kitchen N, Gregg Carlson C, Kleinjan J, Chang J 2007. Using historical management to reduce soil sampling errors. Pp. 49−64. In: Pierce FJ, Clay D ed. GIS applications in agriculture. New York, CRC Press. 203 p.

Coleman K, Jenkinson DS 1996. RothC-26.3—a model for the turnover of carbon in soil. In: Powlson DS, Smith P, Smith JU ed. Evaluation of soil organic matter models. Berlin, Heidelberg, Springer-Verlag. Pp. 237−246.

De Klein CAM, Ledgard SF 2005. Nitrous oxide emissions from New Zealand agriculture—key sources and mitigation strategies. Nutrient Cycling in Agroecosystems 72: 77–85.

Gomez C, Viscarra Rossel RA, McBratney AB 2008. Soil organic carbon prediction by hyperspectral remote sensing and field vis-NIR spectroscopy: an Australian case study. Geoderma 146(3–4): 403−411.

Guo LB, Gifford RM 2002. Soil carbon stocks and land use change: a meta analysis. Global Change Biology 8: 345−360.

Hawke MF 2004. Conversion of forestry land back to production pasture. In: Proceedings of the New Zealand Grassland Association 66: 157−162.

Hedley MJ, Nye PH, White RE 1982. Plant-induced changes in the rhizosphere of rape (*Brassica Napus* var. Emerald) seedlings. New Phytologist 91: 31−44.

Hewitt AE 1998. New Zealand soil classification. Landcare Research Science Series No. 1. Lincoln, Canterbury, New Zealand, Manaaki Whenua Press.

ICF International 2008. Final report: Voluntary carbon market opportunities—soil carbon management in New Zealand. MAF, Wellington, New Zealand, 30 June 2008. 65 p. Available online at www.maf.govt.nz/climatechange/reports/voluntary-carbon-mkt-opps/voluntary-carbon-market-opportunities.pdf (date accessed 14 September 2009).

Jackman RH 1964. Accumulation of organic matter in some New Zealand soils under permanent pasture. Journal of Agricultural Research 7(4): 445−461.

Jorgensen FV, Ledgard SF 1997. Contribution from stolons and roots to estimates of the total amount of N-2 fixed by white clover (*Trifolium repens* L.). Annals of Botany 80(5): 641−648.

Kimberley M, West G, Dean M, Knowles L 2005. The 300 index—a volume productivity index for radiata pine. New Zealand Journal of Forestry 49: 13–18.

Kirschbaum MUF, Guo LB, Gifford RM 2008. Observed and modelled soil carbon and nitrogen changes after planting a *Pinus radiata* stand onto former pasture. Soil Biology & Biochemistry 40: 247−257.

Kusumo BH, Hedley CB, Hedley MJ, Hueni A, Tuohy MP, Arnold GC 2008. The use of reflectance spectroscopy for *in situ* carbon and nitrogen analysis of pastoral soils. Australian Journal of Soil Research 46: 1−13.

Lambert MG, Clark DA, Mackay AD, Costall DA 2000. Effects of fertilizer application on nutrient status and organic matter content of hill soils. New Zealand Journal of Agricultural Research 43: 127−138.

Landcare Research Environmental Chemistry Laboratory 2009. Available online at http://www.landcareresearch.co.nz/services/laboratories/eclab (date accessed 14 September 2009).

Ledgard SF, Steele KW 1992. Biological nitrogen fixation in mixed legume/grass pastures. Plant and Soil 141: 137−153.

Metherell AK 2003. Management effects on soil carbon storage in New Zealand pastures. In: Proceedings of the New Zealand Grassland Association 65: 259−264.

Minasny B, McBratney AB, Mendonca-Santos ML, Odeh IOA, Guyon B 2006. Prediction and digital mapping of soil carbon storage in the Lower Namoi Valley. Australian Journal of Soil Research 44(3): 233−244.

Molloy L 1998. Soils of the New Zealand landscape—the living mantle. 2nd ed. Lincoln, New Zealand, Manaaki Whenua Press.

Morton JD, Roberts AHC 1999. Fertilizer use on New Zealand sheep and beef farms. Auckland, New Zealand. New Zealand Fertilizer Manufacturer's Association. 36 p.

Murty D, Kirschbaum MUF, McMurtrie RE, McGilvray H 2002. Does conversion of forest to agricultural land change soil carbon and nitrogen? A review of the literature. Global Change Biology 8: 105−123.

New Zealand Climate Change Office 2007. Available online at www.climatechange.govt.nz/resources/reports/projected-balance-emissions-jun06 (date accessed 6 August 2009).

New Zealand Ministry of Agriculture and Foresty 2009. http://www.maf.govt.nz/mafnet/rural-nz/sustainable-resource-use/climate/sinks-acitvities (date accessed 14 September 2009).

New Zealand Ministry for the Environment 2009. Reporting under international climate change agreements. Available online at http://www.mfe.govt.nz/issues/climate/lucas/international-agreements.html (date accessed 6 August 2009).

Nguyen ML, Goh KM 1990. Accumulation of soil suphur fractions in grazed pastures receiving long-term superphosphate applications. New Zealand Journal of Agricultural Research 33: 111−128.

Pinno BD, Bélanger N 2008. Ecosystem carbon gains from afforestation in the Boreal Transition ecozone of Saskatchewan (Canada) are coupled with the devolution of Black Chernozems. Agriculture, Ecosystems & Environment 123(1–3): 56–62.

Post WM, Kwon KC 2000. Soil carbon sequestration and land-use change: processes and potential. Global Change Biology 6: 317−327.

Royal Society 2001. The role of land carbon sinks in mitigating global climate change. Royal Society Policy Document 10/01. Royal Society, London. 27 p.

Schipper LA, Sparling GP 2000. Performance of soil condition indicators across taxonomic groups and land uses. Soil Science Society of America Journal 64: 300−311.

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. Global Change Biology 13(6): 1138–1144.

Scott NA, Tate KR, Ross DJ, Parshotam A 2006. Processes influencing soil carbon storage following afforestation of pasture with *Pinus radiata* at different stocking densities in New Zealand. Australian Journal of Soil Research 44(2): 85–96.

Vucetich CG, Wells N 1978. Soils, agriculture and forestry of Waiotapu Region, Central North Island, New Zealand. New Zealand Soil Bureau Bulletin 31, Wellington, New Zealand.

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 Science 87: 135−140.

Wheadon M, Adam B 2006. Forest converter's guide: south Waikato/Bay of Plenty forest to farming project. Fieldbook of Forest to Farming Group Field Day, 27 April 2006, Sustainable Farming Fund, Wellington.