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Soil carbon protection in podocarp/hardwood forest, and effects of conversion to pasture and exotic pine forest

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"Capsule": *The effects of land use change on mineral soil carbon were characterized for New Zealand and soil carbon was found to be significantly related to soil pH.*

Abstract

A combination of paired site, time series, and survey approaches were used to estimate the effect of land use change on mineral soil carbon (C), and to identify factors associated with variation. Land-uses compared included podocarp/hardwood forest, improved pasture, and pine plantation. Soil C was significantly related to soil pH that ranged between 3.9–5.9 (0–0.05 m), 3.6–6.0 (0.05–0.10 m), and 4.5–6.1 (0.10–0.50 m) in indigenous forest. Time series data obtained by periodically re-sampling soil (0–0.10 m) in permanent plots in a pine forest previously under pasture showed that mineral soil C decrease by approximately 4 Mg ha^{-1} by the end of the first rotation. The time series data compared closely with mean results obtained at paired-site throughout New Zealand. Soil C concentration was highly variable in all land-uses, and the evidence suggests that chemical stabilisation of C occurred under acid conditions in native forest, through complexation with Al, and that effects persisted long after conversion of the native forest to other land-uses. The implications of these findings for the design of sampling protocols for soil C are discussed.

Keywords: Soil carbon; Land-use change; Deforestation; Reforestation; Carbon monitoring

1. Introduction

Since 1990 approximately 0.5 million ha of managed pasture has been converted to *Pinus radiata* D.Don plantations in New Zealand. These new forests have the potential to sequester approximately 150 Mg ha^{-1} more carbon (C) than the grassland they replace, taking into account C stored in stems, branches, foliage, roots, and forest floor, including live and dead forest C pools (Beets et al., 1999). Recent studies in NZ reported that surface mineral soil had 20–40% less C under pine relative to pasture for all soils except those with high clay activity where no difference was found (Scott et al., 1999). These results were surprising, and suggested that changes in soil C should be taken into account when calculating carbon sequestration following afforestation of pasture. A preliminary system for all soils has been developed to do this (Scott et al., 1999).

Current land-use and management factors can be expected to influence the upper mineral layers of soil, and the top 0.3 m of mineral soil have been proposed for C inventories by the Intergovernmental Panel for Climate Change (IPCC, 1996). The NZ system (described by Scott et al., 1999) is based mostly on surface (0.1 m) pasture soil data contained in the National Soils Database (McDonald et al., 1988), and pine plantation data from the New Zealand Forest Research Institute soils database. The analysis by Scott et al. (1999) was designed to test whether soil C content was significantly related to current land-use; however, land-use history was unknown and not considered in their analysis. Measurement of the mean residence time of soil organic matter in North America has shown that a large proportion of the surface mineral soil C accumulated while under the natural forests and grasslands that existed prior to colonization by Europeans after 1500 A.D. (Stevenson and Cole, 1999). In New Zealand, it is well known that allophane has a large capacity to protect and hence accumulate C (Jackman, 1964b). Little attention has been placed on the importance of this historical C when designing methods to inventory soil C stocks and estimating the effect of land-use change.

In this paper we compared mineral soil C under indigenous podocarp/hardwood forest, improved pasture, and first rotation *P. radiata* plantation (previously pasture) in adjoining catchments in the Purukohukohu

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Experimental Basin near Taupo, New Zealand (Beets and Brownlie, 1987). Results using a paired-site approach were compared with results obtained by repeat sampling of the pine stand following its establishment on pasture. This land-use comparison study therefore provided the opportunity to assess historical effects on mineral soil C in addition to current land-use effects. Results from Purukokukohu were also compared with predicted changes in surface mineral soil C based on the preliminary system developed using unpaired samples (Scott et al., 2000), and a large set of paired pasture/pine comparisons (compiled by Murray Davis, personal communication). Issues relevant to the development of soil sampling protocols for assessing land use factors associated with land-use change are discussed.

2. Methods and materials

2.1. Purukohukohu Experimental Basin

The Purukohukohu Experimental Basin is located in the Paeroa Range in the central North Island of New Zealand, approximately 30 km south of Rotorua. A description of the vegetation, soil, climate, and pine stand management history is given in Beets and Brownlie (1987). In summary, parent materials originated from Taupo volcanic centre (1860 ± 100 BP) and older ash showers from Taupo and Okataina volcanic centres, which are classified as Pumice Soil in the New Zealand Soil Classification System (Hewitt, 1998). Elevation ranges from 500 to 700 m a.s.l., while topography ranges from gently rolling land with slopes under 12 degrees to moderately steep (slopes up to 23 degrees) to steep (slopes up to 30 degrees). Soils belong to the Oruanui series, and are highly permeable, with loamy sand, silty sand, and gravel (Taupo lapilli). Topography has had a major influence on erosion and hence the thickness of the pumice layers (Rijkse and Bell, 1974). Rainfall averages 1500 mm per year, and temperature averages 10 °C, with monthly averages ranging between 5 and 15 °C.

The basin includes three land-use catchments (Fig. 1). Maps giving boundaries between the main land-use catchments and Puruki pine subcatchments were published previously (Beets and Brownlie, 1987).

1. Puruorakau (37.2 ha): indigenous mesophyll forest, classified as mixed podocarp/tawa (McKelvey, 1963). The indigenous forest catchment includes large individual podocarp trees, including rimu (*Dacrydium cupressinum* Lamb.) and miro (*Prumnopitys ferruginea* (D. Don) de Laub.), which can be 500–800 years old. No logging has occurred within the majority of this catchment.
2. Purutaka (22.5 ha): developed in 1957 into improved pasture grazing sheep and cattle, after original clearing of native forest in the 1920s reverted to seral scrub. Pasture management involves regular applications of superphosphate fertiliser, and the use of legumes (clovers) to fix nitrogen. In anticipation of planting pines, no fertiliser was applied to the pasture in Puruki catchment since 1969.
3. Puruki (35.4 ha): as for Purutaka but with a land-use change from pasture to *Pinus radiata* in 1973 when the stand was established at an initial stocking of 2200 trees ha^{-1}, and fenced to exclude grazing animals. Puruki catchment is subdivided into three subcatchments (1 = Tahi, 2 = Rua, 3 = Toru), to which different thinning regimes were applied. The understory was dominated by tall pasture species for the first 3 years, but was largely suppressed following canopy closure at stand age six. Bracken fern was the dominant understory vegetation following thinning, particularly in Tahi which had the lowest final stocking (60 trees ha^{-1}), and where vigorous bracken fern persisted over the rotation. In Rua (final stocking of 550 trees ha^{-1}) and Toru (final stocking of 160 trees ha^{-1}) the understory was sparse by stand age 20, and was comprised of ferns and scattered native shrubs.

2.2. Land-use transect soil samples

Transects (each 200–300 m long) were installed from ridge crest to gully to opposing ridge crest in each land-use, with two transects installed in the pine catchment, and one each in the pasture and native forest catchments. Transects were installed so they would be as comparable as possible in terms of altitudinal range and topography, because the statistical analysis was based on the assumption that soil C in each catchment reflects current land-use, and that possible historical land-use effects could be ignored. This assumption underlies any paired-site study.

In March 1993 soil cores were collected at 20–30 m intervals along each transect, from 0–0.05, .05–0.10, and 0.10–0.50 m depths. Cores were 60 mm in diameter (for surface samples) or 98 mm in diameter (0.1–0.5 m samples). Two cores were taken at each depth (one for bulk density, the other for chemistry) from an area of approximately 1 m^2, and soil air-dried and sieved (< 2 mm fraction) to remove roots, fragments of wood and bark, and lapilli. Mineral soil clods were forced through the sieve. Fine roots became fragmented during processing and some inevitably pass through the sieve, particularly in pasture soils. Soil C (expressed as g C/100 g oven dry soil) was determined by thermal combustion (Leco CNS-2000, LECO Corp., St Joseph, Michigan, USA), and pH was determined in water. Fine earth (< 2

Fig. 1. Purukohukohu land-use catchments located mid-way between Taupo and Rotorua, central North Island, New Zealand. The entire area was originally covered with indigenous forest until the 1920s. The area reverted to shrubland, until improved pasture was developed in the 1950s. The pasture was converted to pine in 1973.

mm fraction) bulk density was determined after oven drying soil to constant weight at 105 °C. Soil C content (Mg C/ha) was calculated from the C concentration and bulk density of the fine earth fraction for each depth.

2.3. Time series soil samples following land-use change from pasture to pine

Thirty randomly located permanent sample plots (PSP No. 1–30) were established in the Puruki catchment to monitor stand development as part of another study of pine productivity (Beets and Brownlie, 1987). Plots were initially circular 0.01 ha in area, but were increased to 0.04 ha after thinning of subcatchments from 2220 trees ha^{-1} down to 550 trees ha^{-1} in 1979 (Tahi), 1980 (Rua), and 1981 (Toru). Plots were allocated to subcatchments in proportion to subcatchment area. Ten soil cores (0–0.10 m depth) were collected with a Hoffer sampler from each plot in 1978, 1979, 1980, 1982, 1995, and 1996 when the pine stand was 5, 6, 7, 9, 22, and 23 (23 for Rua only) years old. Sampling followed a grid pattern, with the 10 cores bulked by plot, and air dried, sieved (<2 mm fraction), and C determined by thermal combustion. Two additional cores (0–0.10 m depth) were collected from each plot using a 60 mm diameter sampler, dried to constant weight at 105 degrees C, and fine earth bulk density (<2 mm fraction) determined.

The 30 PSPs provided direct evidence of the effect of land-use change from pasture to pine on surface mineral soil C from the time when the pasture understory was largely suppressed to the end of the first rotation. Possible artificial effects associated with live root fragments passing through the sieve when the soil supports pasture is avoided during this time period, but some loss in soil C may have already occurred.

2.4. National paired-site data

Paired comparisons at forty sites under pasture and adjacent conifer plantations (mostly first rotation radiata pine on ex-pasture soils with high clay activity), showed that surface mineral soil C concentration (<2 mm fraction down to 0.10 m depth) under pine averaged 0.92 of that under pasture (Murray Davis, personal communication). Bulk density was measured at 21 of these sites, where C under pine averaged 0.92 and 0.93 of pasture values based on C concentration and C content, respectively. The importance of having paired samples was considered to over-ride possible issues surrounding methodology differences among studies. For example, the intensity of sampling varied markedly (typically four pits per site, ranging from 1 to 20 cores or pits per site and land-use). Plantation age averaged 22 years since establishment on pasture, but ranged mostly between 15 and 30 years old. Stocking ranged from 270 to 7500 trees ha^{-1}.

The results of the time series data from Puruki are shown together with data from the national paired sites, to aid comparison.

2.5. National soil chemistry survey

Soil chemical properties were measured in 9–26 year old pine stands growing mostly on level uniform sites selected from areas expected to cover a wide range of soil type and climate, as part of a *P. radiata* productivity study (Jackson and Gifford, 1974). Soils were classified according to the New Zealand genetic classification (NZ Soil Bureau, 1968). Soil bulk density was not measured.

C, Bray aluminium (Al), total phosphorus (P), and P-retention were determined in a composite sample of 7–10 cores (0–0.075 m of mineral soil) from each of the 128 (0.04 ha) plots following analytical procedures described in Ballard (1978a). Foliar nutrients in 1-year-old needles from second order branches in the mid-crown were measured in seven dominant trees per plot (Ballard, 1978b). Previous analysis of these data focussed on predicting soil P-retention (Ballard, 1978a), and relationships between foliar cation concentrations and soil cation measures (Ballard, 1978b). These data offered the opportunity to explore relationships between soil C concentration and soil chemistry and fertility, as reflected by foliar nitrogen N concentration.

2.6. Statistical analysis and presentation of results

The land-use transects, Puruki time series, and national soil survey data were examined using the SAS GLM procedure. The analysis was based on soil C content, when dealing with C stocks. Soil C concentration was used to examine variation in relation to pH, to facilitate comparisons with the national soil chemistry data, for which bulk density was not measured. The use of soil C concentration are justified on the basis of the paired-site results, which clearly showed that land-use effects were almost identical using either soil C concentration or content, because bulk density was not affected by afforestation (Murray Davis, personal communication).

When analysing the Puruki catchment time series data, the effect of time on soil C content (i.e. years since pasture was converted to pine), was tested by averaging data for years 5–9, and 22–23. Stand age class, subcatchment, and age class$\times$subcatchment interactions were examined. The effect of stand age class on soil C in the repeatedly measured PSPs was expected to provide the most robust analysis of effects of land-use change from pasture to pine. The effect of subcatchment provided insights into soil C variation at a scale of approximately 10 ha. The interaction provided information on effect of stand silvicultural management on soil C. The overlay of the time series data from Puruki on the national paired-site data provides information on the generality of the Puruki results to other soil types.

The national soil survey data under pine plantations provides information on broad scale variation in soil C. The effects of soil type, P-retention, Bray Al, total P, and foliar N on soil C concentration were examined using the SAS GLM procedure. Bray Al and P-retention were expected to strongly reflect the influence of native vegetation pre-dating the pines.

3. Results

3.1. The Purukohukohu Experimental Basin

3.1.1. Land-use transects

Soil C concentration along the land-use transects is shown in Fig. 2. The most striking feature is the high spatial variation evident in all land-uses. The GLM analysis showed that soil C concentration varied markedly with depth and soil pH, but was not significantly related to land-use (Table 1). However, a statistically significant though weak land-use $\times$ depth interaction was found, with surface soil under pasture containing more and sub-surface soil less C than forest. The mineral soil C content down to a total depth of 0.50 m is given for each land-use catchment in Fig. 3.

Soil pH along the land-use transects is shown in Fig. 4. The large range in pH over small distances was again, striking. In native forest, low pH was found when rimu litter in particular occurred in the forest floor material overlying the soil sample. In general, variation in subsoil pH reflected variation in surface soil pH ($r=0.82$,

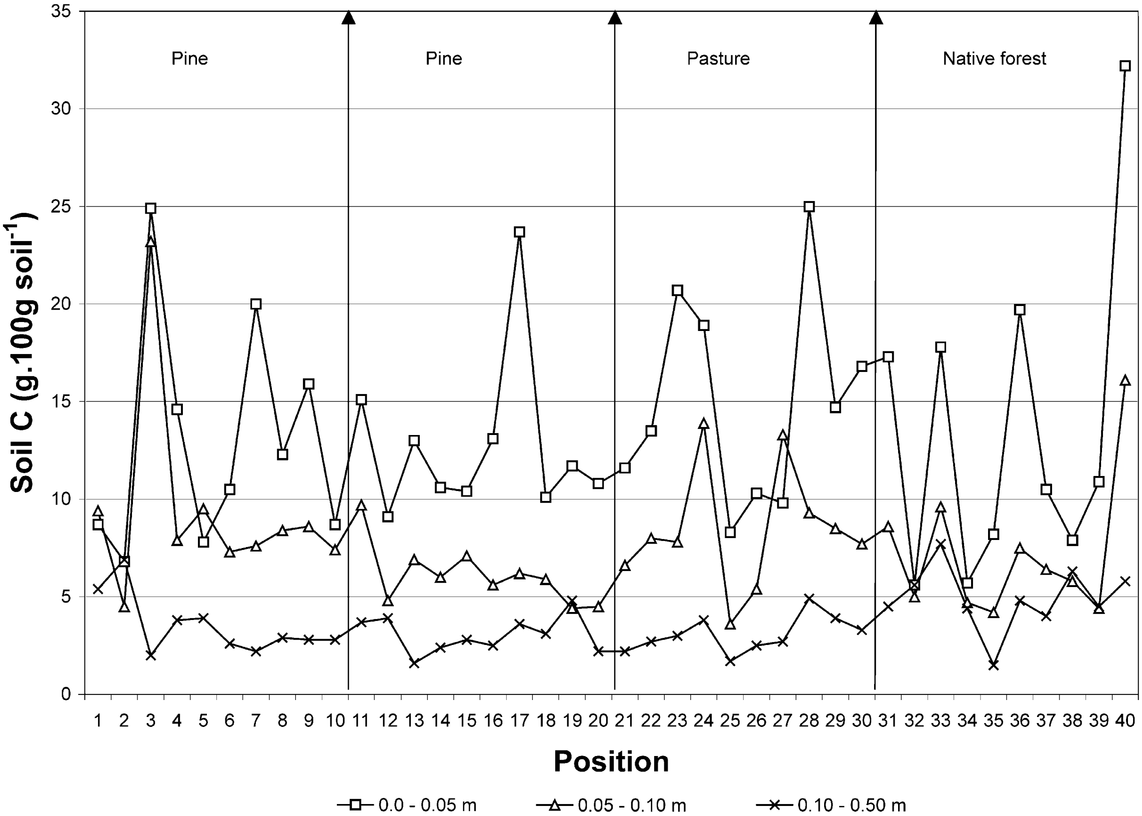

Fig. 2. Soil carbon concentration at 20–30 m intervals along land-use transects at Purukohukohu, including along two transects through pine forest, and one transect through pasture and unlogged mature native forest.

Table 1
Factors associated with variation in soil C concentration along land-use transects (including native forest, pasture, pine), all originally under native forest[a]

Factor	DF	SS	MS	*F* value	Prob. > *F*
Land-use	2	0.09	0.05	1.4	0.242
Depth	1	2.99	2.98	95.7	0.0001
pH	1	0.53	0.53	16.9	0.0001
Land-use×depth	2	0.232	0.116	3.7	0.028

[a] The model has an R^2 of 67%.

prob.=0.01, n=10) under native forest, but not under pasture or pine. Soil mean pH was not related to land-use, however, the range in pH was in the order native forest > pine > pasture. The relationship between soil C concentration and pH is shown by land-use in Fig. 5, which shows that the reduction in the range of soil pH in pasture was not associated with a reduction in the range of soil C concentration.

3.1.2. Time series studies following land-use change

Analysis of the time series data from the PSPs in Puruki catchment (Table 2) indicated highly significant subcatchment, plot, and stand age class effects on top-soil C content. The subcatchment×stand age class interaction was not significant, which suggests that the tree stocking differences at the end of the rotation did not modify the effect of stand age class. Least squares means and standard errors of carbon content (Table 3) show that the reductions in C content over time were similar in magnitude to the differences in C content among subcatchments.

3.2. Paired site land-use comparisons

Soil carbon data from paired studies throughout New Zealand (compiled by M. Davis, personal comunication) are shown in Fig. 6. The Puruki PSP time series data are superimposed, with the plot C content at stand age 5 years shown as "pasture" and the age 22-year data shown as "pine". This portrayal of the Puruki time series data shows that soil C content is generally lower after 22 years of pine growth following pasture, which is consistent with results obtained from paired site comparisons, which both show that surface mineral soil C content under pine averages 0.9 of pasture values. Variability in the data is high, which is partly associated with sampling error. At Puruki, for example, only 10 cores were bulked from each plot at each age (Fig. 6).

The predicted land-use factor (0.65) based on unpaired soil samples in the National Soils Database (Fig. 6), is clearly inconsistent with the land-use change

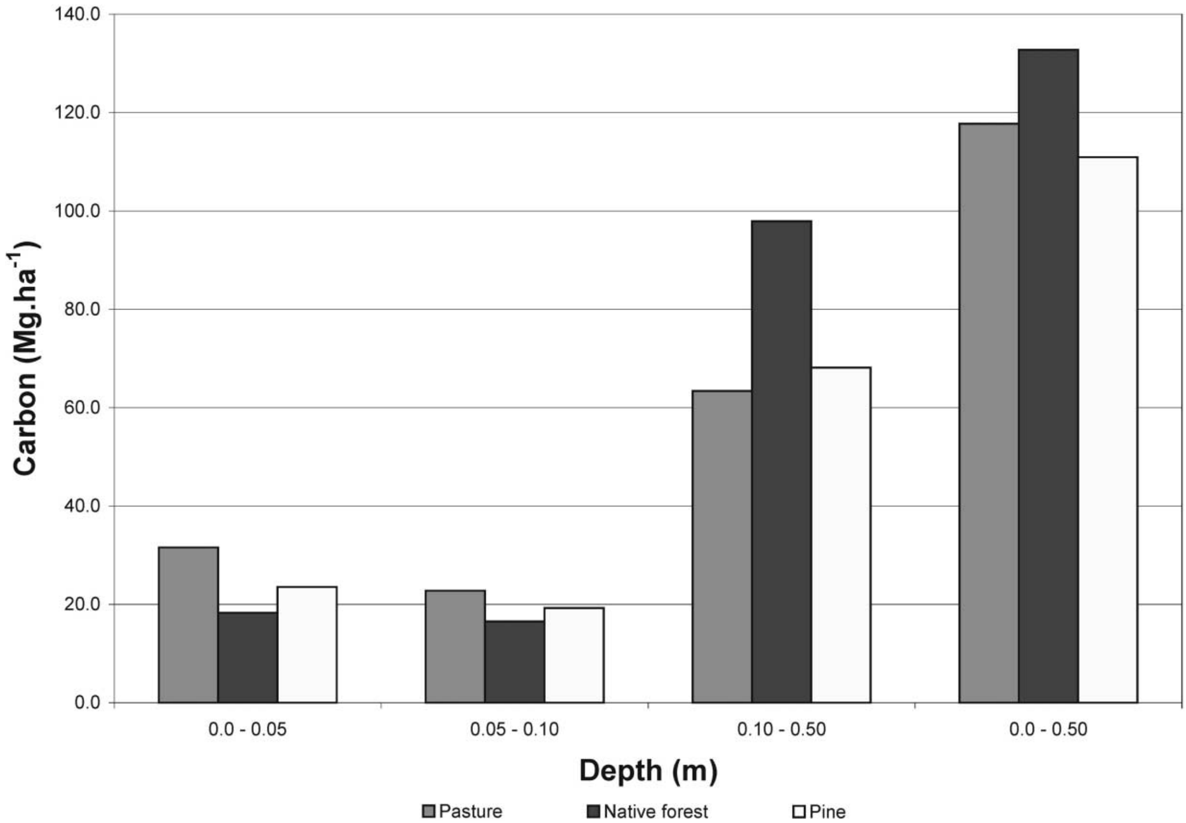

Fig. 3. Soil C content by depth increment at Purukohukohu land-use transects.

Table 2
Factors associated with variation in topsoil C content in pine subcatchments at Puruki 23 years following the conversion of Puruki from pasture[a]

Factor	DF	SS	MS	F value	Prob. > F
Subcatchment	2	275.7	137.8	14.9	< 0.0001
Plot (within subcatchment)	27	1798.4	66.6	7.2	< 0.0001
Stand age class	1	184.0	184.0	19.9	0.0001
Stand age class × subcatchment	2	38.2	19.1	2.1	0.1472

[a] The three subcatchments were at markedly different final tree stockings. The catchment was historically under native forest prior to the 1920s. The model has an R^2 of 90%.

factor (0.90) obtained from the national paired-site studies and the Puruki time series data.

3.3. Soil chemistry survey

Analysis of the national soil chemistry data showed that variation in soil C was linearly related to P-retention, which alone accounted for 68% of the variation in surface mineral soil C concentration in pine stands distributed throughout New Zealand (Fig. 7). Ballard (1978a) previously showed for these same soils under pine, and Jackman (1964[b],b) and Saunders (1965) for other soils under developed pasture, that soil P-retention, C, and Al were highly correlated with each other and increased approximately in the order of soil weathering.

The GLM analysis of the pine data showed that soil C is associated with a number of factors in addition to soil type (Table 4). Furthermore, 90% of the contribution made by soil type on its own was accounted for by P-retention, with the latter accounting for considerably more variation than soil type on its own. Bray Al was significantly related to soil C but did not make a significant independent contribution after P-retention was taken into account, however, total P and foliar N jointly accounted for an additional 3% of the variation.

4. Discussion

Soil C stocks in New Zealand were recently predicted from the National Soils database (NSD) using an enhancement of the default IPCC methodology (Scott et al., 2000). This system is largely based on carbon measurements from unpaired pasture and forest soil samples obtained throughout New Zealand. Analysis of the database showed that soil C content under pine forest was approximately 0.65 of that under improved pasture, other factors (soil type, climate using GLM statistical procedures) being equal. The land-use factor representing

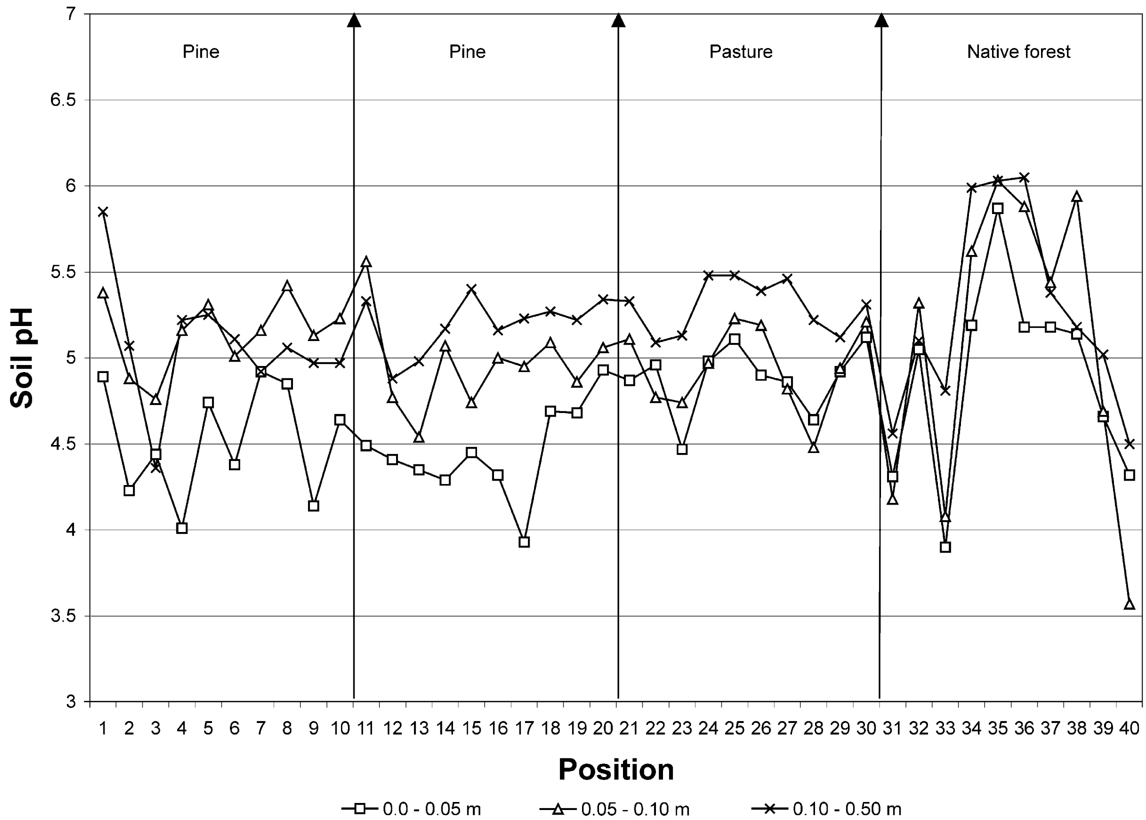

Fig. 4. Soil pH at 20-30 m intervals along land-use transects at Purukohukohu.

Table 3
Mineral soil C content and standard error (Mg ha^{-1}, to 0.10 m depth) in the Puruki subcatchments soon after canopy closure and 23 years following establishment of pines[a]

Subcatchment	Stocking trees ha^{-1}	C content (at 5–9 years)	S.E.	C content (at 21–23 years)	S.E.	Prob. > t
Tahi	60	38.3	0.96	34.4	0.96	< 0.0001
Rua	550	44.5	1.15	39.0	1.15	< 0.0001
Toru	160	40.8	0.84	39.3	0.84	< 0.0001
Overall	220	41.2	0.57	37.6	0.57	< 0.0001

[a] The native forest at Puruki was cleared in the 1920s and established into pasture, which was subsequently planted with pine in 1973.

the change in land-use from pasture to pine (0.65), when applied to a site with 150 Mg ha^{-1} of soil C under pasture, predicts soil C under pine would decrease by approximately 50 Mg ha^{-1}. The overall sequestration of carbon following afforestation of pasture with radiata pine would therefore be predicted to reduce from 150 Mg ha^{-1} when soil is excluded to 100 Mg ha^{-1} when soil C is included.

Such a large loss in soil carbon following conversion of pasture to pine is not supported by results from either our time series data or the large set of paired-site studies described in this paper. Surface mineral soil C can be expected to decrease by 4–5 Mg ha^{-1} following the conversion of pasture to pine. This decrease applies to the first rotation. No suitable soil data were available to indicate trends in second and subsequent rotations.

A key premise of the unpaired sample approach is that soil C attains an equilibrium value under a particular climate/soil/land-use type. The classification of the New Zealand landscape into climate/soil/vegetation types, while useful when accounting for broad scale effects of variation in soil chemistry and weathering on soil C, is apparently insufficient to account for bias within a climate/soil type associated with using unpaired samples. We suggest that historical factors play a major role in protecting mineral soil C for considerable length of time, including after land-use change. It is well known that tree species differentially influence soil pH at small spatial scales (Ovington and Madgwick, 1957; Zinke, 1962), which in turn influences weathering and dissolution of Al, and hence the protection of C at local and regional scales. The strong association between

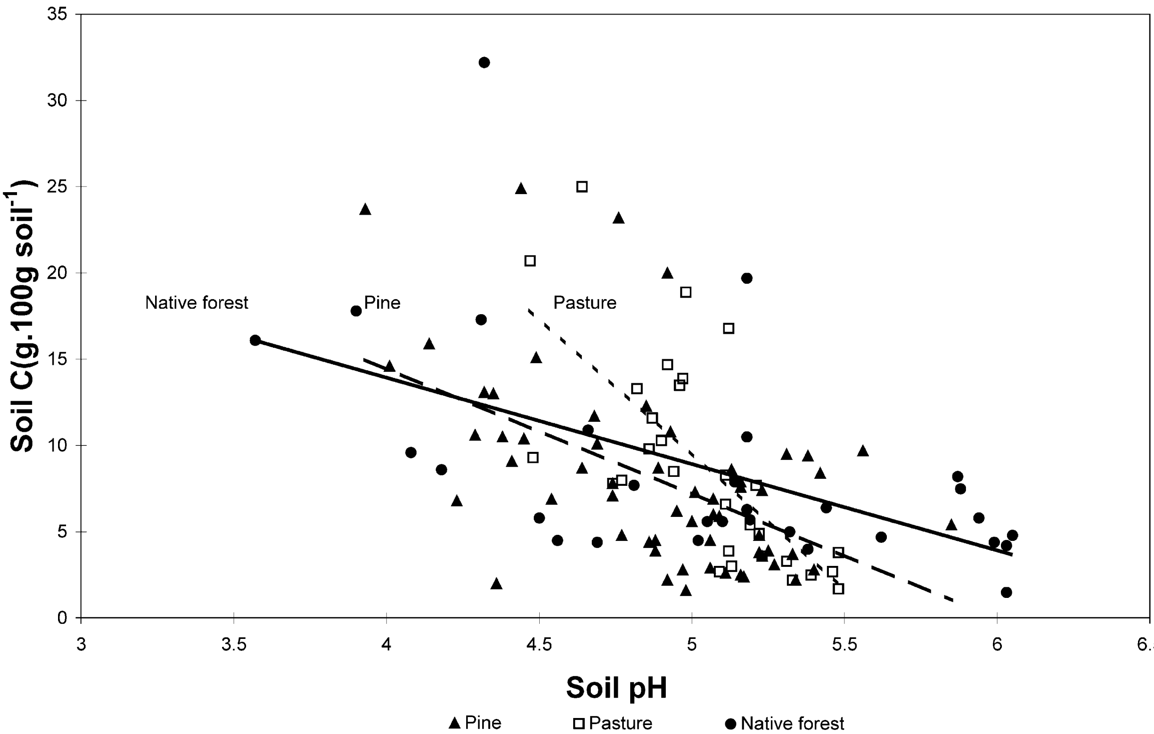

Fig. 5. Soil C concentration in relation to pH at Purukohukohu land-use catchments.

surface mineral soil C concentration and Al and P-retention is consistent with the formation of Al/humic acid complexes, perhaps along the lines proposed by Yuan et al. (2000).

Complexation developed under native forest is very durable in volcanic and perhaps other soils, and is expected to largely determine both the amount and variability of soil C in pasture and pine sites for a considerable time after the clearance of native forest. Variability in surface mineral soil C is usually ascribed to an imbalance between soil C gains and losses from recent litter inputs and decomposition. This may be true for the 4–5 Mg ha^{-1} of surface mineral soil C lost across all subcatchments at Puruki. However, we suggest that historical factors dating back hundreds or thousands of years need to be taken into account for most of the mineral soil C, owing to the formation of stable mineral-humus complexes (Stevenson and Cole, 1999). Saunders (1965) provides an illuminating discussion of the relationship between soil C and Tamm Al (determined at pH 3.5), as a basis for interpreting results of his own research into variability of soil C under pasture. Clearly, historical vegetation cover largely influences variation in soil C currently under pasture, and we conclude that our results are therefore applicable to a large proportion of the New Zealand landscape, whether currently under native forest, plantation forest or pasture. In future, measures such as soil P-retention may provide an independent method for assessing historical factors underlying the protection of soil C, as soil C and P-retention are both related to Al (Bohn et al., 1979).

Little change in soil C occurs after 20 years under continuous pasture (Jackman, 1964a), though nitrogen fertility and rainfall appear to influence current C inputs and soil C stocks (Nguyen et al., 1989; Nguyen and Goh, 1990). The C content of the pasture catchment at Purukohukohu is therefore expected to have been largely stable over the last 20 years. Comparing land-uses (pasture versus pine catchment) at Purukohukohu yielded a greater difference in soil C compared to the time series data from Puruki. This can be explained by initial differences in the historical C stocks between the catchments prior to planting the pines. The significant effect of subcatchment on soil C at Puruki support this view, because all subcatchments had the same land-use history. Using the NSD, the assumption that soil C was initially equal is not likely to be valid, even if many comparisons are made—differences in the historical C content under the land-uses being compared may preclude this. In contrast, many paired-site comparisons should give an acceptable estimate of the effect of land-use change provided that sites free of land-use deployment biases are selected. Ideally, land-use effects on soil C need to be derived independently from soil survey data, using appropriate sampling designs and extrapolation methods.

The effects of soil erosion require additional consideration because erosion displaces some of the historical C associated with the original native forest trees.

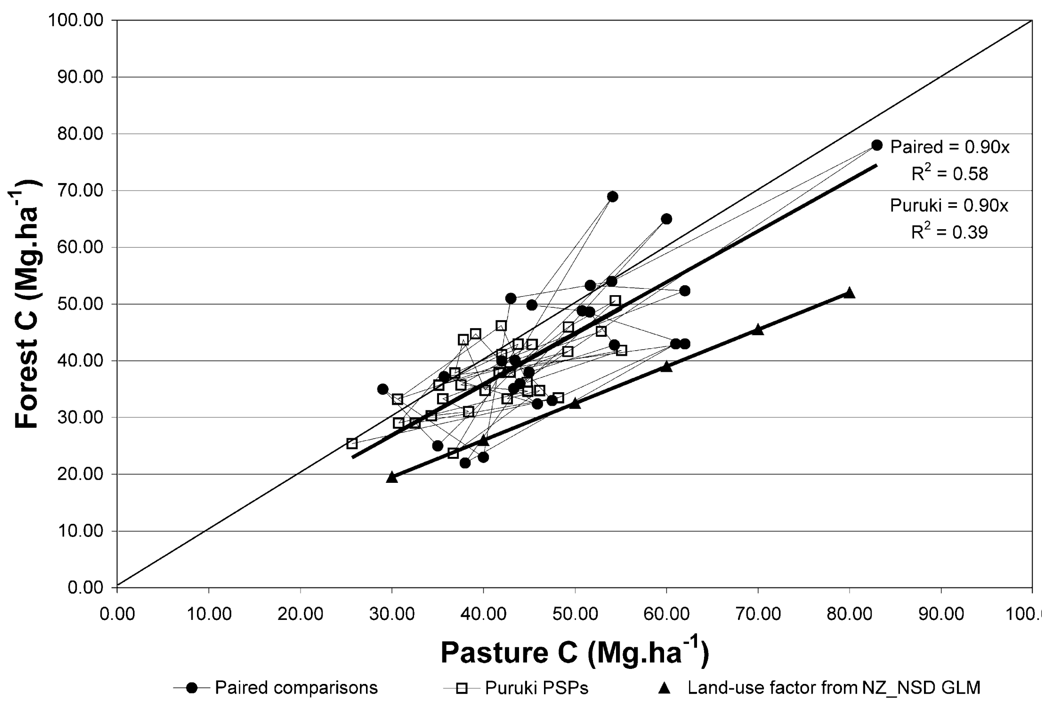

Fig. 6. Soil carbon content at paired-sites distributed nationally, with the Puruki time series data superimposed.

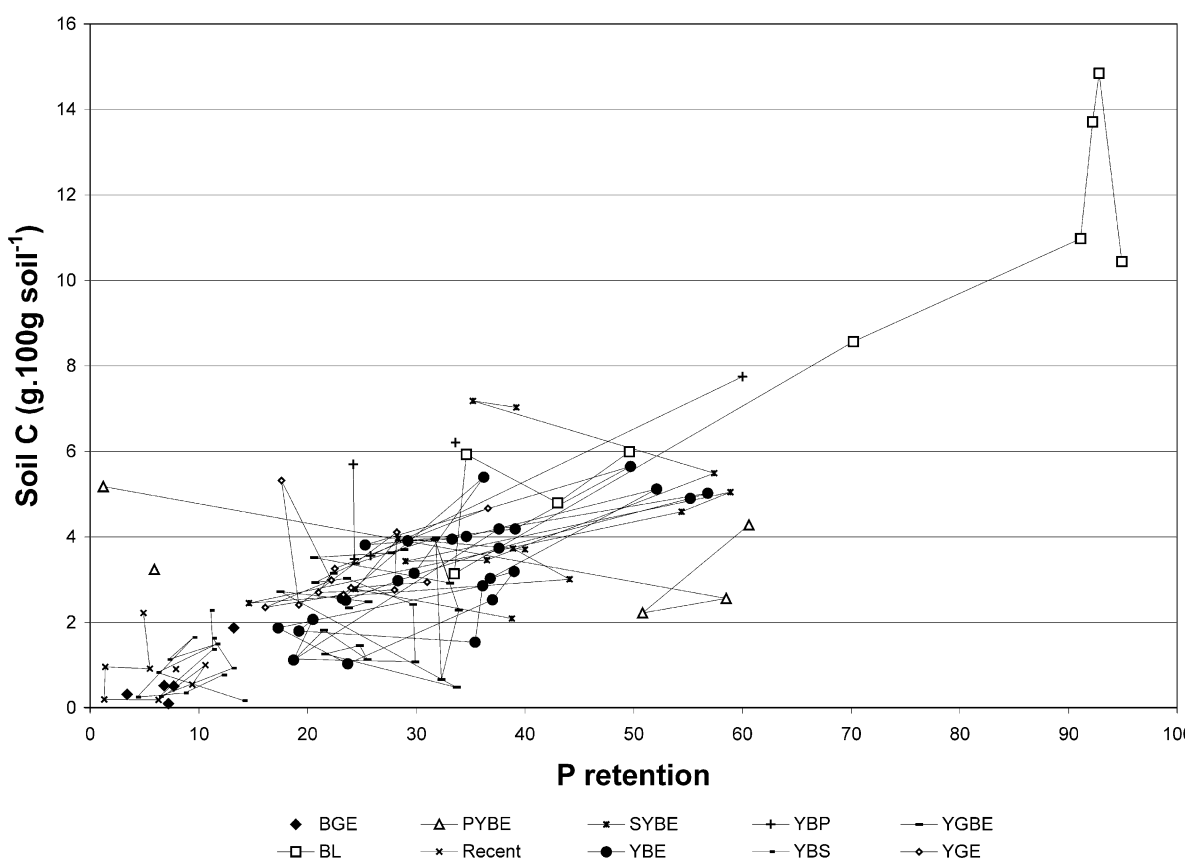

Fig. 7. Soil C concentration in relation to P retention, based on a national survey of pine plantations in New Zealand.

Table 4
Factors associated with variation in topsoil C concentration in *Pinus radiata* stands throughout New Zealand[a]

Factor	DF	SS	MS	*F* value	Prob. > *F*
Soil type	10	60.6	6.06	4.3	< 0.0001
P-retention	1	64.4	64.4	45.6	< 0.0001
Total P	1	12.6	12.6	8.9	0.0035
Foliar N	1	7.2	7.2	5.1	0.0256

[a] The model has an R^2 of 79%.

The pasture sward in the studies reported here was apparently effective in preventing major erosion of the soil following forest clearance. These results are therefore expected to be applicable to surface soil under stable improved pasture. In contrast, if land-use comparisons are made at severely eroding pasture sites, where establishment of pines reduces soil erosion (as is prevalent in the Gisborne region of New Zealand), a different land-use factor may be expected, and the derived factor would best be described largely as an erosion factor.

Most results reported here apply to the top 0.10 m of mineral soil. Monitoring to greater depths is likely to be essential when quantifying changes in soil C following a land-use change from pasture to pine, because the root systems of trees extend beyond that for improved pasture species. This may explain why the soil C content was greater under the native forest than pasture when the profile was sampled to greater depths. Furthermore, considerable redistribution of soil C occurs during forest harvesting operations, particularly when ground-based harvesting systems are used, with soil disturbance clearly extending beyond the 0.30 m depth suggested by the IPCC. A land-use factor should ideally not be confounded by C redistribution associated with harvesting operations.

5. Conclusions

1. Soil C is very variable both within and among soil types throughout New Zealand.
2. Soil C is related to pH, with spatial variability in historical soil C greater than current land-use change effects.
3. Land-uses can be validly compared when historical differences in soil C are removed by appropriately pairing a sufficient large number of sites.
4. Soil surface (0–0.10 m) C content under stable pasture is greater than under pine by approximately 4–5 Mg ha^{-1} based on (repeatedly measured) time series data and paired-site comparisons.
5. Possible management effects on soil C content, for example mixing of logging slash and forest floor material during harvesting and site preparation operations, are unclear, and depth of sampling needs further consideration. Soils should be sieved to remove slash and forest floor material, to avoid double accounting when determining stand total C.
6. Unpaired land-use comparisons can be misleading, because they may reflect initial differences in the magnitude of historical soil C content rather than the desired land-use effect.

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Murray Davis kindly allowed us to show the results of a compilation of paired pasture/pine comparisons in relation to our time series data following land-use change from pasture to pine. These two data sets nicely complement each other, and add strength to both his and our results. We express our appreciation to Dr. D.S. Jackson who was responsible for the national pine productivity survey as part of which the soil samples were collected, and Mark Kimberley who assisted with the statistical analysis of the survey data. This paper was presented at the USDA Forest Service Southern Global Change Program sponsored Advances in Terrestrial Ecosystem: Carbon Inventory, Measurements, and Monitoring Conference held 3–5 October 2000 in Raleigh, North Carolina.

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