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

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ABSTRACT

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

1. Introduction

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

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

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

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

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

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

2. Methods

2.1. Site selection

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

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

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

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

2.2. Data analysis

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

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

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