Radiocarbon Evidence for Contrasting Soil Carbon Dynamics in a Andisol and Non-Andisol Pasture Soil Comparison

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Abstract

In 1959, Athol Rafter began a substantial programme of monitoring the flow of ^{14}C produced by atmospheric thermonuclear tests through New Zealand's atmosphere, biosphere and soil. A database of over ~400 soil radiocarbon measurements spanning 50 years has now been compiled. A key comparison within the dataset is described here, providing quantification of the differences in soil C dynamics between Andisols and non-Andisols. We use ^{14}C to quantify soil carbon turnover parameters in deforested dairy pastures under similar climate in the Tokomaru silt loam (non-Andisol) versus the Egmont black loam (Andisol), originally sampled in 1962, 1965 and 1969. After adding surface soils sampled to a similar depth in 2008, we use a 2-box model to calculate that the residence time of stabilized soil C in the Tokomaru soils is ~9 years compared to ~17 years for the Egmont soils. This difference represents nearly a doubling of soil C residence time, and roughly explains the doubling of the soil C stock. With three measurements in the 1960s, and an assumption of a 1000 year residence time for passive soil C in the surface layer, the data is of sufficient resolution to estimate that passive soil C comprises 15% of the soil C pool in Tokomaru soils versus 27% in Egmont soils. The Tokomaru/Egmont comparison is necessarily illustrative since neither site was replicated extensively, but does provide globally unique data. The comparison supports evidence that C dynamics does differ in Andisols versus non-Andisols, as a result of both the mineral allophane and Al complexation.

Introduction

In 1959, Athol Rafter began a substantial programme of monitoring the flow of ^{14}C produced by atmospheric thermonuclear tests through New Zealand's atmosphere, biosphere and soil. The "bomb-^{14}C" augments the natural cycling of ^{14}C, overlaying annual and decadal resolving power onto the centennial and millennial resolution obtained from radioactive decay (half-life = 5730 years). The programme produced important publications (e.g. O'Brien and Stout, 1978) and leaves a legacy of unpublished data critical for understanding soil C dynamics. A database of over ~400 soil radiocarbon measurements spanning 50 years has now been compiled. This time-series ^{14}C data provides an opportunity to quantify soil C dynamics in the C pools that interact with atmosphere at decadal timescales. These pools have been included in most terrestrial ecosystem biogeochemistry models, yet concerns remain that conceptual pools used in models cannot be isolated and quantified (Baisden and Amundson, 2003; Bruun et al., 2009). Multi-decade ^{14}C datasets and modeling provide a clear and compelling approach that allows the dynamics of conceptual soil C pools to be quantified without the chemical or physical isolation of C fractions specifically representing the conceptual soil pools. The use of time-series ^{14}C datasets therefore creates the opportunity to quantify how models should represent proposed differences between C dynamics in Andisols and non-Andisols (Torn et al., 1997; Parfitt, 2009).

This work builds on research showing that bulk soil and the separation of 2 soil fractions on the basis of density quantifies soil C turnover for the main soil C pool with approximately the same degree of certainty as a more complex separation into 5 density fractions (Baisden et al., 2002a). Model estimates of

C turnover calculated using time-series ^{14}C data as a function of depth under pasture in a New Zealand silt loam soil (Dystrochrept) found that ‘active’, ‘stabilized’ (decadal) and ‘passive’ (inert) pools comprise 10, 75 and 15% of total soil organic C (Baisden and Parfitt, 2007). The nature of radiocarbon as a decadal and millennial tracer, combined with the relatively small size of the active pool and large size of the stabilized pool in New Zealand soils emphasizes the opportunity to undertake modeling that assumes the active pool is negligible, and calculates residence times and pool sizes for the large stabilized and passive C pools.

Key aspects of time-series soil ^{14}C datasets are described here, with an emphasis on quantifying the differences in soil C dynamics between Andisols and non-Andisols (as defined by USDA soil classification). In particular, we focus on comparison of soil carbon dynamics in deforested dairy pastures under similar climate in the Tokomaru silt loam (non-Andisol) versus the Egmont black loam (Andisol), originally sampled in 1962, 1965 and 1969. Here, we add measurements for surface soils sampled to a similar depth in 2008 and calculate residence times for the major pools of C present in surface soil. We examine the calculated residence times in terms of observed flow of carbon through the pastures and the size of soil C stocks.

Methods

In this work, we collate information obtained over nearly 50 years from an “experiment” effectively identified during the 1960s by researchers interested in using ^{14}C to identify differential rates of C cycling in pasture soils with and without substantial presence of volcanic mineralogy delivered by andesitic tephra (Figure 1). Egmont loam soils (Hapludands) were sampled within 50 km of the tephra source, Mt. Taranaki (also known as Mt. Egmont). Tokomaru silt loam soils (Fragiaqualfs) were sampled 150-200 km to the southeast where the soil parent material was dominated by quartzo-feldspathic loess, and the soil contains no allophane. Climate and pasture production are similar in the two locations (Roberts and Thompson, 1984; Radcliffe, 1976). Mean annual soil temperature for both sites is ~12˚C and mean annual rainfall in the range of 1000-1300 mm. During the period 1962-1969, soils were collected using 12 2.6 cm soil cores per site, to a depth of 8 cm, as reported in Jackman (1964) and Schipper and Sparling (2009). Later soils were collected from soil pits either as part of New Zealand Soil Bureau soil survey activities, or using similar methods (Schipper et al., 2007) and are part of ^{14}C studies as a function of soil depth to be reported elsewhere. The 2008 Egmont sample is 0-5 cm.

All Δ^{14}C data is reported as defined in Stuiver and Polach (1977) and is the result of combusting soil samples to CO_2 and subsequent ^{14}C determination at the Rafter Radiocarbon Laboratory and its predecessor. Values reported are for <2 mm soil with live roots removed and no chemical treatment. For samples collected prior to 1980, gas proportional counting was used, while more recent samples were analyzed using accelerator mass spectrometry (EN-Tandem). All Δ^{14}C values obtained from gas proportional counting have been recalculated using original counting statistics. In all cases, analytical error is ≤6‰. Additional samples from the Tokomaru and Egmont pastures established in 1870 and 1900, respectively, were collected and measured in 1971 but have been excluded from

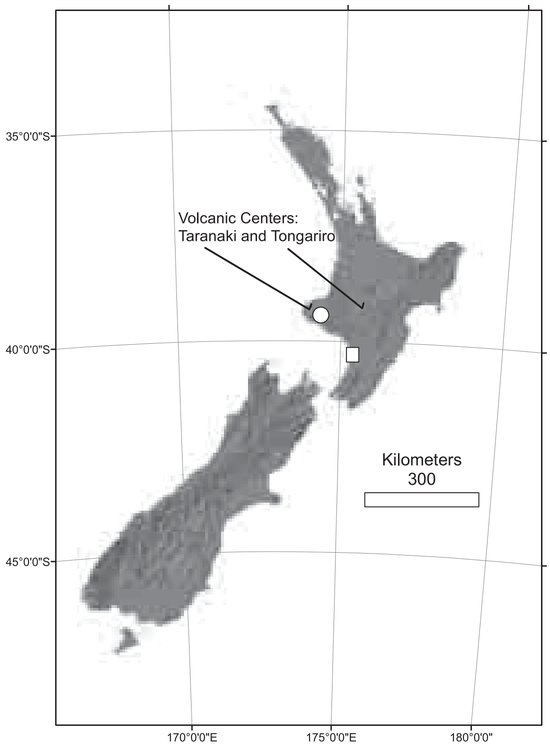

Fig. 1. The location of Egmont (circle; Andisol) and Tokomaru (square; non-Andisol) soils relative to the main volcanic centers generating tephras.

this work because these samples alone were treated with hot 2% phosphoric acid and the Tokomaru data shows a pronounced depression (223‰) while the Egmont data shows a mild depression (124‰) relative to the data shown in Figure 2. The comparison between the Egmont and Tokomaru soils was initially made as a comparison between pastures established in 1870-1900 versus 1945. Where ^{14}C data existed for sites with different ages of pasture establishment, the data were averaged for modeling as shown in Figure 2.

We estimated the turnover rate of SOM based on measured Δ^{14}C values using an approach identical to Baisden et al. (2002a) and Prior et al. (2006). The approach recognizes that two 'pools' of SOM with different residence times can exist within the same soil or soil fraction. We assume one pool (C_{pool}) has annual to decadal residence times while the other pool ($C_{passive}$) is passive (millenial turnover times). The model assumes that both pools have reached steady state, meaning that the inputs, *I*, are equal to the outputs, defined as the residence time, *k*, multiplied by C_{pool}. Starting in 1909, the model numerically incorporates C with a ^{14}C/^{12}C ratio representing the atmospheric CO$_2$ incorporated in plant biomass, taken from Southern Hemisphere atmospheric data (Currie et al., 2009).

$$\frac{\Delta C_{pool}}{\Delta t} = \left(I - kC_{pool}\right)\Delta t \qquad (1a)$$

$$\frac{\Delta\left({}^{14}C_{pool}\right)}{\Delta t} = \left(A_{year-lag} I - (k+\lambda)^{14}C_{pool}\right)\Delta t \qquad (1b)$$

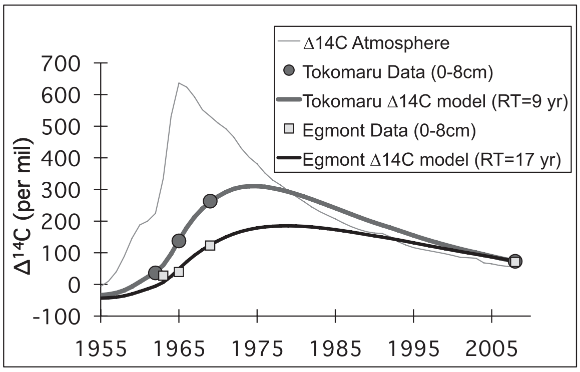

Fig. 2. Variation in Δ^{14}C in the Egmont (Andisol) and Tokomaru (non-Andisol) soils over the last 50 years.

In these equations, C_{pool}, and $^{14}C_{pool}$ represent SOC mass and ^{14}C mass in a portion of the soil fraction, while Δt represents a timestep and is generally one year. Note that Δ in these equations applies the difference operator and not isotope notation. The ^{14}C/^{12}C ratio of the atmosphere, $A_{year\text{-}lag}$, is lagged behind the atmospheric data by 0.25 year to represent the approximate residence time of C in plant biomass. The decay constant for radiocarbon (λ) is set to $1.21\text{x}10^{-4}$ y^{-1}. The Δ^{14}C of the passive pool was calculated based solely on radioactive decay (λ) and assumed residence time, and the Δ^{14}C of the modelled fraction is calculated as the mixture of the passive pool ($C_{passive}$) and C_{pool} in equations 1a and 1b according to the following equation.

$$\Delta^{14}C_{soil} = (1 - P_{passive})\Delta^{14}C_{pool} + P_{passive}\Delta^{14}C_{passive} \qquad (2)$$

$P_{passive}$ is the fraction $\left[C_{passive} / \left(C_{passive} + C_{pool}\right)\right]$ of the SOC in the sample which is passive C. The Δ^{14}C value of the passive fraction was poorly constrained by the model, and therefore set for each soil to a residence time of 1000 y (Δ^{14}C = -110‰). The model was implemented in Microsoft Excel with an annual time step. The values of k and $P_{passive}$ were fitted to the data using Microsoft Excel's 'solver' (www.solver.com). The optimized fit minimizes the sum of squared errors between the modelled and measured fraction Δ^{14}C obtained for each year a sample was available. Testing for impact of possible changes in soil C content as reported in Schipper et al. (2007) using the non-steady state model described in Neff et al. (2009) showed that where time-series ^{14}C data are available, small or negligible (<10%) impacts on calculated residence times occur. Varying the residence time chosen for passive C causes the size of the passive fraction to vary proportionally, but has a small effect on the residence time of the stabilized pool for passive residence times of 1000 years or more.

Results

Considerably greater bomb-^{14}C uptake is observed in the 0-8 cm layers of the Tokomaru silt loam than in Egmont silt loam (Figure 2). The simple 2-box model calculates that the residence time of stabilized soil C in the Tokomaru soils is 9 years compared to 17 years for the Egmont soils. This difference represents nearly a doubling of soil C residence time, and roughly explains the doubling of the soil C stock from approximately 45 to 75 Mg C ha^{-1} in the Tokomaru and Egmont 0-8 cm layers, respectively, as sampled by Jackman (1964). With three measurements in the 1960s, and an assumption of a 1000 year residence time for passive soil C in the surface layer, the data is of sufficient resolution to estimate that passive soil C comprises 15% of the soil C pool in Tokomaru soils versus 27% in Egmont soils. The range of values calculated is broadly consistent with soil C models (e.g., Parton et al., 1987), and previous ^{14}C studies (e.g., Baisden et al., 2002a,b). The greater quantity of passive soil C in the Andisol is consistent with previous New Zealand studies, which indicated the differences in the proportion of passive C between an Andisol and non-Andisol were more dramatic when summed over the upper 20 cm of soil (Parfitt et al., 1997; Parfitt et al, 2002). Both enhanced stabilized pool residence times and passive soil C pool sizes are consistent with the view that Andisols or soils with allophanic mineralogy enhance soil C storage (Torn et al., 1997; Parfitt, 2009).

Based on the soil C pool sizes and calculated residence times, the throughput of C through the stabilized pool is relatively more similar across the soils, calculated as 3.4 and 4.4 Mg C ha^{-1} y^{-1} for the Egmont and Tokomaru soils, respectively. This is a substantial fraction of net primary productivity (NPP), based on figures for aboveground NPP obtained by repeated pasture clipping of 5 Mg C ha^{-1} y^{-1} for both sites (Roberts and Thompson, 1984; Radcliffe, 1976).

Discussion

The difference between rates of bomb-^{14}C uptake in the surface layer of the Andisol (Egmont) and non-Andisol (Tokomaru) is clear, and can be inferred to correspond directly to the rate of C turnover through the soil. Using a simple 2-box model, excellent fits are obtained to the data (Figure 2) suggesting a near doubling of residence time in the Andisol relative to the non-Andisol, which corresponds to a near doubling of the C stock. It is notable, however, given suggestions that stabilization of soil C by the mineral allophane may be responsible for enhanced soil C stocks in Andisols (Torn et al., 1997) that the effect on stabilized C residence times is not more dramatic. Indeed, allophane may account for a larger passive pool in the Andisol. Because of the larger C stock in the Andisol and the near doubling of the passive fraction calculated using ^{14}C data, the size of the passive pool in the Andisol appears to be 3-4 times that in the non-Andisol. In contrast, the enhanced residence time of stabilized soil C in the Andisol may correspond to the higher exchangeable Al levels associated with Andisols, which contribute to soil C stabilization through complexation (Parfitt, 2009).

The contrasting C dynamics observed in the Andisol and non-Andisol emphasize the potential of ^{14}C to constrain C dynamics, and elucidate directions for further research. First, compiling and understanding datasets spanning 50 years requires considerable effort to compile and reconcile information. Efforts should be made to better understand the differences between results obtained on carefully resampled sites and those obtained across soil mapping units. At present, both approaches appear valid. Second, efforts to understand sources of variability affecting soil Δ^{14}C would be valuable. At this stage, it appears that the soil C pool may not always be at steady-state (Schipper et al, 2007; Bellamy et al., 2005). While long-term trends affecting soil C stocks have been tested and found to have little impact on residence times calculated with time-series ^{14}C data, year-to-year variation in pasture production may be worthy of exploration as a means to improve model fitting following suggestions that it may cause transient variations in soil C stocks (Schipper et al, 2009), and therefore potentially Δ^{14}C data obtained during years immediately following the bomb-^{14}C spike. Finally, although modeling soil C dynamics as a function of depth involves greater complexity (Baisden and Parfitt, 2007), this surface 0-8 cm dataset represents only a beginning to true understanding of soil C dynamics. Efforts to partition NPP between respiration and stabilization of C in soil, with subsequent transformations and transport of stabilized soil C, remains an important requirement of integrated C-cycle studies.

The Tokomaru/Egmont comparison is necessarily illustrative since neither site was replicated extensively, but provides globally unique data. Moreover, the Tokomaru/Egmont comparison supports evidence that C dynamics does differ in Andisols versus non-Andisols. Additional lines of evidence include emerging theories of soil organic matter stabilisation processes, rates of soil organic matter change following land-use change, and chemistry data. The results presented here suggest C turnover parameters representing soil mapping units can be compiled empirically using ^{14}C, and that time-series samples may present a more useful alternative to physical or chemical fractionation schemes. This finding is particularly useful given that the contrasting soil C dynamics in these different soils appear to have implications for land-use change and management schemes that could be eligible for "C credits".

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