Significant bomb ^{14}C enrichment in deep soil: a previously unrecognized decadal C pool?

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Abstract
Globally, soil organic matter contains approximately 1500 Pg C to 1 m soil depth and 2300 Pg C to 3 m depth—more than biomass and atmospheric CO_2 combined. Efforts to account for the effects of land-use or vegetation change on soil organic carbon (SOC) stocks normally limit their focus to the upper 20–30 cm of the soil profile, yet 0–20 cm SOC stocks are only 42% of 0–1 m SOC. Accounting for only the upper 20–30 cm of SOC has been justifiable based on the assumption that deeper SOC is unreactive since it displays ^{14}C-derived mean residence times of hundreds or thousands of years. We report that, at depths of 40–100 cm, a well-studied New Zealand soil displays progressive enrichment of over 200‰ across samplings in 1959, 1974 and 2002, indicating incorporation of bomb ^{14}C during the last 40 years. This pattern of deep ^{14}C enrichment—previously observed in two well-drained California grassland soils—suggests that roots and/or dissolved organic C (DOC) transport contribute to a Decadally-Reactive Deep Soil C (DRDSC) pool. This SOC pool can react to land-use or vegetation change.

Key Words
Soil organic matter (SOM), carbon, radiocarbon, land-use change, dissolved organic carbon (DOC).

Introduction

The Kyoto Protocol and the subsequent Marrakesh accords require accurate accounting of the responses of vegetation C and SOC to land-use change and forestry (LUCF). It has been assumed that SOC changes related to LUCF occur almost entirely in the upper 30 cm of soil, because deep SOC is inert on timescales <100 years and is transported slowly downward relative to plant sources (Baisden et al., 2002a, O'Brien and Stout, 1978). As a result of these assumptions, most ecosystem biogeochemistry models that estimate the response of vegetation and soil to climate change, land management, and other factors, consider C dynamics in only the upper 20–30 cm of soil. Yet, estimates of SOC stocks generally recognize that SOC below 30 cm is a significant stock, and that SOC is distributed somewhat more deeply than plant roots (Jobbagy and Jackson, 2000).

Since little mechanistic understanding exists to explain deep SOC dynamics, we resampled a New Zealand grassland soil for which now classic models of SOC turnover and transport were developed (O'Brien and Stout, 1978). We therefore add soil radiocarbon measurements performed to ~1 m depth from 2002 to measurements performed in 1959 and 1974. These measurements occur over a time period ideal for calculating the turnover rates of decadal C pools using the natural ^{14}C-enrichment of the atmosphere from thermonuclear weapons testing—a near doubling of atmospheric ^{14}C/^{12}C ratio in 1963 (Trumbore, 1993).

Methods

Site and Sampling

The Judgeford, Riverbank and Turlock Lake sites (Table 1) have been described elsewhere (O'Brien and Stout, 1978, Lassey et al., 1996, Baisden et al., 2002a, Harden, 1987). Briefly, the Judgeford soils were under indigenous forest cover until European colonization of New Zealand, and have been converted to *Agrostis capillaris* dominated grassland for ~100 years. The Riverbank and Turlock Lake sites are dominated by annual grasses, but had a greater cover of native perennial grasses before ~150 years ago. None of the three sites has received significant inputs of N or P fertilizer.

The 1974 and 2002 samplings of the Judgeford soils occurred at locations ~1 km and ~200 m distant from the original site, at sites with nearly identical topography and soil horizonation. For the 2002 sampling, a matching site was carefully chosen based on stable land-use history, since the 1959 site has undergone

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disturbance. Samples were taken from a soil pit, and sieved to remove roots >2 mm. Bulk density was measured by coring. No stones were encountered.

Table 1: Site Descriptions

Site	Soil Age	Soil Parent Material	Mean Annual Temp.	Mean Annual Precip.	Surface Soil Texture
Judgeford (O'Brien and Stout, 1978) New Zealand	~15 ky	Quartz/ Feldspathic Loess	12.6°C	1290 mm	Silt Loam
Riverbank (Baisden et al., 2002a) California, USA	~200 ky	Granitic Alluvium	16°C	300 mm	Sandy Loam
Turlock Lake (Baisden et al., 2002a) California, USA	~600 ky	Granitic Alluvium	16°C	300 mm	Loamy Sand

Modelling

We model the dynamics of C and ^{14}C in the soil profile using a 3-pool mass balance model that recognizes C inputs from the surface litter and roots, downward transport, and turnover (oxidation) of each C pool (Baisden et al., 2002a). To account for the apparent downward transport and retention of bomb-^{14}C below 30 cm depth, which was also observed in two well-drained California grassland soils (Baisden et al., 2002a), we added a fourth pool of SOC to the model. We term this pool Decadally-Reactive Deep Soil C (DRDSC). DRDSC was empirically modeled based on four parameters: the total amount of DRDSC; a characteristic (e-folding) depth used to adjust an exponential depth distribution; a downward transport rate; and a decomposition rate constant for the pool. The representation for DRDSC was not connected to the other 3 pools and does not represent a mass-balance model. Instead, it provides the minimum degrees of freedom required to fit the observed increase in $\Delta^{14}C$ observed below 30 cm soil depth. In contrast to previous studies providing estimates of SOC turnover rates for the three pool model (Baisden et al., 2002b, Baisden et al., 2002a), we optimized the model presented here to determine the mass and turnover rates of the SOC pool associated with bomb-^{14}C enrichment observed below 30-cm depth. Atmospheric $\Delta^{14}C$ data for the southern hemisphere were obtained from a spline fit to the Baring Head, New Zealand data (Manning et al., 1994).

The %C and $\Delta^{14}C$ estimated by the model for all 4 pools of SOC was optimized in MATLAB (The MathWorks, Natick, MA, USA) using the Genetic Algorithm Toolbox (University of Sheffield, 1994). Solutions represent the fittest individuals from multiple runs of a single population of 50 real-valued chromosomes evolved over >300 generations. We used intermediate recombination with a hypercube 50% larger than the difference between reproducing individuals. The genetic algorithm was rerun with random variation in $\Delta^{14}C$ (normal distribution; σ=5‰) and %C (log normal distribution; σ=5% COV) to estimate uncertainty and sensitivity. For the Judgeford site, plant C inputs were allowed to vary within bounds (aboveground inputs between 0.5 and 1 x average aboveground NPP, belowground inputs between 0.5 and 3 x aboveground NPP) established based on field sampling(Saunders and Metson, 1971). For the Turlock Lake and Riverbank sites, measured plant C inputs were used, but varied with random variation (normal distribution; σ=15‰) to estimate uncertainty and sensitivity. Uncertainties reported in Table 2 and Supplementary Table S1 represent the greater of either the standard deviation of the 50 individual estimates from the genetic algorithm or the difference between the fittest individual obtained without random variation and the mean of the individuals obtained with random variation.

Table 2: Parameter values and uncertainty. All parameters, excluding the 4 describing DRDSC, are defined identically to those in previous modeling (Baisden et al., 2002a).

Parameter	Explanation	Units	Judgeford	Riverbank	Turlock Lake
$1/k_1$	active pool residence time	y	3.34±0.09	0.50±0.06	0.50±0.05
$1/k_2$	stabilized pool residence time	y	51±4	21±2	25±3
$1/k_3$	passive pool residence time	y	12000±2000	9300±500	>35,000**
k_{t1}	partitioning coef.	--	0.32±0.01	0.09±0.01	0.08±0.01
$k_{t2}/1000$	partitioning coef.	--	0.34±0.09	0.29±0.04	0.43±0.10
f_s	surface litter C inputs	gC m^{-2} y^{-1}	265±10	282*	178*
R	root C inputs	gC m^{-2} y^{-1}	408±91	279*	357*
v_1	active pool downward velocity	mm y^{-1}	6.2±1.3	0.6±0.2	0.5±0.4
v_2	stabilized pool downward velocity	mm y^{-1}	0.9±0.3	1.3±0.1	0.5±0.1
v_3	passive pool downward velocity	mm y^{-1}	0.19±0.01	0.25±0.01	0.50±0.05
L	e-folding depth for root inputs	cm	29±3	35±1	9±1
1/P	rate of relocation of passive SOC to surface	y	13400±400	123000±9000	49000±7000
D_p	$\Delta^{14}C$ of passive SOC relocation	‰	-600±31	-520±54	-323±48
C_{DRDSC}	normalized concentration of DRDSC	--	0.39±0.11	0.05±0.01	0.10±0.04
V_{DRDSC}	downward velocity of DRDSC	cm y^{-1}	3±97***	14±9	9±25***
$1/k_{DRDSC}$	residence time of DRDSC	y	1.0±1.0***	1.0±0.2	11±22***
L_{DRDSC}	e-folding depth of DRDSC	cm	623±797	565±67	668±327

*Above and belowground vegetation C inputs were measured directly at these sites, rather than modeled.
**Model result indicated an age greater than ages detectable by radiocarbon measurements.
***High uncertainties for these parameters indicate multiple model solutions were possible "on either side" of the bomb-^{14}C spike.

Results and Discussion

Within the upper 30 cm, the measurements display expected values: $\Delta^{14}C$ values were just below 0‰ in 1959, strongly enriched by bomb-^{14}C in 1974, and returning toward the pre-bomb values in 2002 (Figure 1). However, at depths of 40–100 cm the time-series profiles display a surprising and progressive enrichment of up to 200‰ over the 43 years. While it is possible that this enrichment could have resulted from site selection, a similar but smaller enrichment was observed in both of the well-drained California grassland soil profiles (Baisden et al., 2002a). In support of our finding, 10 years after ^{14}C labeling of Colorado short-grass prairie, 17.5% of recovered ^{14}C tracer was found below 50 cm soil depth (Gill et al., 1999).

Parameter values from the 3-pool SOC model were not sufficiently different from previous results (Baisden et al., 2002b, Baisden et al., 2002a) for the two California soils to warrant further discussion given the purpose of this study (Table 2). Parameter values for the Judgeford soil (Table 2) differ approximately as expected from those determined for the California soils given the differences in climate and soil parent material (Table 1). The parameter values are within the range expected based on existing models such as CENTURY and RothC (Parshotam, 1996, Parton et al., 1996, Smith et al., 1997).

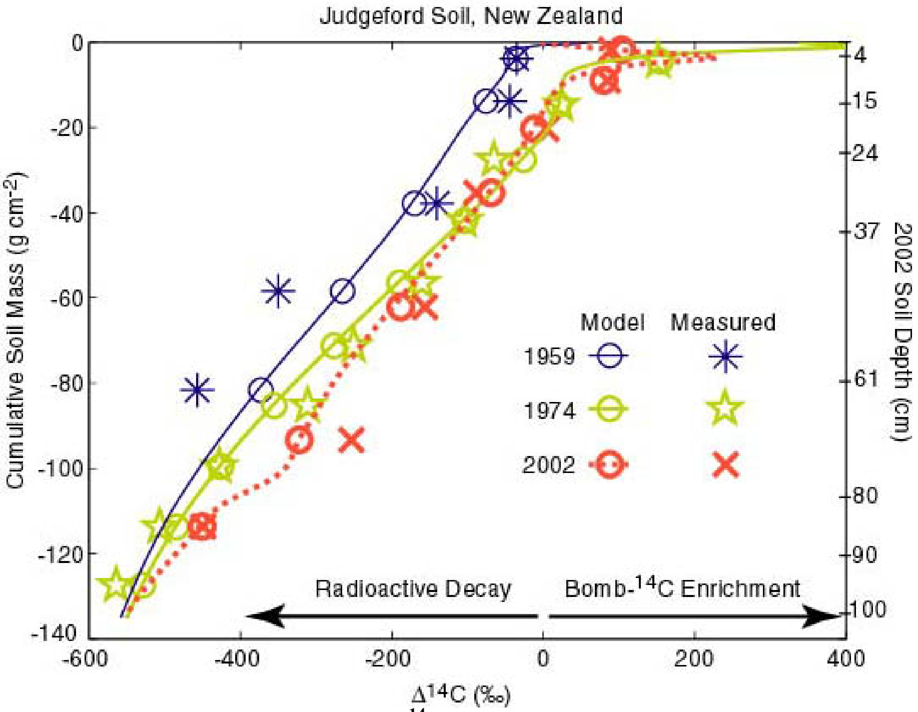

Figure 1. Observed and modelled $\Delta^{14}C$ values for the 1959, 1974 and 2002 samplings of the Judgeford soil profile, New Zealand. Radiocarbon data are expressed in $\Delta^{14}C$ notation, corrected for isotopic fractionation using $\delta^{13}C$ data. We use the notation $\Delta^{14}C_{sample} = (^{14}C/^{12}C_{sample})/(^{14}C/^{12}C_{standard}) - 1$, where the standard is 95% of the activity of NBS Oxalic Acid—approximately representing the composition of pre-industrial atmosphere. Cumulative soil mass is equivalent to soil depth in centimeters with bulk density normalized to 1 g cm^{-3}.

Figure 1 demonstrates that the model captures the general pattern of variation seen in soil $\Delta^{14}C$ as a function of soil depth. However, the model does not fully account for deep bomb-^{14}C enrichment, particularly in the Judgeford soil where this enrichment is ~200‰. The inability of the model to capture the full bomb-^{14}C enrichment most likely results from the model's assumption of uniformity of processes as a function of soil depth. For example, hydrologically driven transport rates are known to decrease with soil depth as plants remove water from the rooting zone and return it to the atmosphere via transpiration. Soil biological processes can also be expected to vary with soil depth as a result of non-linear effects of soil temperature and moisture (Metherell et al., 1993). Figure 1 demonstrates that the model captures the general pattern of variation seen in soil $\Delta^{14}C$ as a function of soil depth. However, the model does not fully account for deep bomb-^{14}C enrichment, particularly in the Judgeford soil where this enrichment is ~200‰. The inability of the model to capture the full bomb-^{14}C enrichment most likely results from the model's assumption of uniformity of processes as a function of soil depth. For example, hydrologically driven transport rates are known to decrease with soil depth as plants remove water from the rooting zone and return it to the atmosphere via transpiration. Soil biological processes can also be expected to vary with soil depth as a result of non-linear effects of soil temperature and moisture (Metherell et al., 1993).

The model calculations suggest that the DRDSC represents 5–23% of total SOC within the sampled soil profiles, and 8–74% of SOC with turnover rates of years to decades (Table 2). Moreover, the lower end of these estimates probably underestimates the true size of the DRDSC because the model does not fully account for the deep bomb-^{14}C enrichment observed in the Judgeford soil (Figure 1), and because the DRDSC extends below the soil depths sampled in this study. The likely sources of DRDSC carbon are deep plant roots and dissolved organic matter (DOM) transport.

Recognition of the DRDSC challenges studies of the terrestrial C cycle by potentially doubling the size of SOC pools, which are understood to react on timescales <100 years to LUCF and climate change in grasslands, and perhaps other terrestrial ecosystems. Improving our knowledge of the DRDSC will be critical for improving models of SOC cycling (Baisden et al., 2002a) to include SOC turnover and transport below 30 cm depth—an essential aspect of C accounting (Jobbagy and Jackson, 2000, Jackson et al., 2002). Further research will require radiocarbon measurements in additional soils as well as the development of independent mechanisms of estimating DRDSC in soils with greater variation in natural abundance $\Delta^{14}C$, including colluvial upland soils and forest soils. Improved understanding will result primarily from investigations of processes controlling the transport and fate of organic matter in soil.

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