SYNTHETIC CONSTRAINT OF SOIL C DYNAMICS USING 50 YEARS OF ^{14}C AND NET PRIMARY PRODUCTION (NPP) IN A NEW ZEALAND GRASSLAND SITE

W Troy Baisden[1] • E D Keller

National Isotope Centre, GNS Science, New Zealand.

ABSTRACT. Time-series radiocarbon measurements have substantial ability to constrain the size and residence time of the soil C pools commonly represented in ecosystem models. ^{14}C remains unique in its ability to constrain the size and turnover rate of the large stabilized soil C pool with roughly decadal residence times. The Judgeford soil, near Wellington, New Zealand, provides a detailed 11-point ^{14}C time series enabling observation of the incorporation and loss of bomb ^{14}C in surface soil from 1959–2002. Calculations of the flow of C through the plant-soil system can be improved further by combining the known constraints of net primary productivity (NPP) and ^{14}C-derived C turnover. We show the Biome-BGC model provides good estimates of NPP for the Judgeford site and estimates NPP from 1956–2010. Synthesis of NPP and ^{14}C data allows parameters associated with the rapid turnover "active" soil C pool to be estimated. This step is important because it demonstrates that NPP and ^{14}C can provide full data-based constraint of pool sizes and turnover rates for the 3 pools of soil C used in nearly all ecosystem and global C-cycle models.

INTRODUCTION

Time-series radiocarbon measurements have substantial ability to constrain the size and residence time of the soil C pools commonly represented in ecosystem models (Parton et al. 1987; Jenkinson 1990; Baisden and Amundson 2003). Understanding the nature of soil C and its response times to disturbances including land-use change and climate has been and remains a top priority in the science required to develop predictive understanding of the global C cycle (Jenkinson et al. 1991; Trumbore 2009). ^{14}C remains unique in its ability to constrain the large stabilized C pool with decadal residence times, across a range of soils. ^{14}C also contributes usefully to constraining the size and turnover rate of the passive pool, but typically struggles to constrain pools with residence times less than a few years. Overall, the number of pools and associated turnover rates that can be constrained depends upon the number of time-series samples available, the appropriateness of chemical or physical fractions to isolate unequivocal pools, and a series of critical assumptions (Trumbore 2009; Baisden et al. 2013).

A major complication in the use of ^{14}C data to constrain soil C dynamics has been understanding turnover and transport as a function of soil depth (Baisden et al. 2002; Baisden and Parfitt 2007; Jenkinson and Coleman 2008). However, recent work has shown that ^{14}C-derived turnover times from bulk soil in surface horizons can be consistent and representative of much wider depth increments in New Zealand grassland soils (Baisden and Canessa 2013; Baisden et al. 2010, 2013), opening the way for wide use of relatively simple time-series bulk-soil ^{14}C measurements to constrain the parameters describing the 3 pools of soil C commonly represented in models. This work describes the use of net primary productivity to assist time-series ^{14}C data at a well-studied site in constraining the dynamics of the fast-cycling "active" soil C pool, as well as the "stabilized" (decadal) and "passive" or "inert" (millennial) pools.

[1]Corresponding author. Email: t.baisden@gns.cri.nz.

Proceedings of the 21st International Radiocarbon Conference edited by A J T Jull & C Hatté
RADIOCARBON, Vol 55, Nr 2–3, 2013, p 1071–1076

METHODS

High-Resolution Time Series in the Judgeford Soil

Data reported for the Judgeford soil under grazed pasture is as reported in O'Brien and Stout (1978) and Baisden and Parfitt (2007). Briefly, the site is at 41.1°S with mean annual rainfall of ~1300 mm and soils are of a silt-loam texture. The 1973 and 2003 sampling sites differ slightly from those used earlier due to disturbance (Baisden and Parfitt 2007).

Pasture NPP – Measurement and Modeling

Pasture productivity at the well-studied Judgeford site was measured as part of studies to determine the impact of topsoil mining on pasture production and soil fertility (Hart and August 1988; Hart et al. 1989). All data used for this study was from control treatments representing normal agricultural practices, and has been recovered from laboratory reports. Pasture production was measured according to the widely used methods of Radcliffe (1974) using harvests of aboveground biomass obtained from animal grazing enclosure cages. Using these methods, estimates of NPP can be depressed somewhat from optimal values due to the initial biomass after the previous harvest and declining growth combined with litter production over long periods. The harvest periods in this study were long, and therefore assumed to slightly underestimate true aboveground production under grazing. Total NPP has been calculated assuming that dry matter harvested is 50% C by mass, and that total NPP including belowground root growth is twice that of aboveground NPP. In this study, the site-based NPP data are used only to verify that the independent estimates provided by the Biome-BGC model are reasonable.

Model estimates of NPP are preferred over the limited period of measurements because grassland NPP is highly dependent on year-to-year and season-to-season climate variability. We use the Biome-BGC model v 4.2 (Thorton and Rosenbloom 2005) to estimate grassland NPP for the site based on climate data from nearby stations for 1956–2010. The model has been calibrated to New Zealand sites with long-term pasture production data (Keller et al. 2011). Three sites have been used for calibrating sheep and beef grazing land representing the type of agriculture land use at the Judgeford site, using the PEST parameter estimation software (www.pesthomepage.org).

Soil Radiocarbon Model

A spreadsheet-based box model similar to that presented in Baisden et al. (2013) has been used, with the following changes. The stabilized pool has been implemented so that a steady state is no longer assumed, and each year's inputs have been scaled to vary in proportion to NPP in that year, while maintaining the correct long-term average. Similarly, an active pool has been added to the model, so that the long-term average size of the active pool is an adjustable parameter, and the size of the active pool in any given year is proportional to NPP in that year. All inputs are assumed to have the ^{14}C equivalent to that year's atmosphere as recorded in Currie et al. (2011). The NPP prior to the study period was assumed to be equivalent to the 1956–2010 average. The total soil C stock was set to match the observed soil C stock of 14.6 kg m^{-2} within the upper 30 cm, calculated as the average stock from multiple samplings of the site at different times.

The simple combination of a soil C stock and an NPP model describing time-dependent inputs to soil C pools provide an opportunity for synthesis. The soil C stock is split into 3 pools and a turnover rate applied to each pool, which should then match the long-term average rate of C inputs. This assumption lies between a true steady-state model and a fully dynamic model, and is consistent with the assumption that the turnover times (yr) of each soil C pool are the inverse of the turnover rate

(yr^{-1}). Synthetic constraint was provided by using the solver in Microsoft Excel to minimize the sum of squared errors resulting from the following model-data comparisons. First, each soil ^{14}C measurement was compared with an associated modeled value. Second, the total flow of C through the system obtained by multiplying the size of each soil C pool by its turnover rate was compared to NPP. The latter measurement was calculated in kg m^{-2} yr^{-1} and scaled by a factor of 200 within the sum of squares calculation to make the relevance of NPP errors comparable to the sum of 11 ^{14}C model-measurement comparisons.

RESULTS AND DISCUSSION

The comparison of measured to modeled aboveground NPP at the Judgeford site is shown in Figure 1. Based on the comparison shown, the available data from pasture production measurements are considered to verify the model outputs in terms of aboveground production. It must be noted, however, that no measurements of root production have been made at Judgeford, and the assumption that total production is twice aboveground production remains a major source of uncertainty. With this assumption, total NPP estimated from the New Zealand implementation of the Biome-BGC model averages 1.26 kg C m^{-2} yr^{-1} during the period 1956–2010.

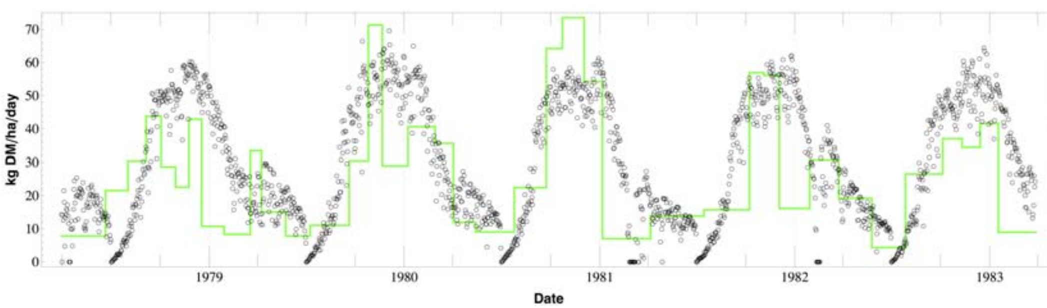

Figure 1 Pasture production measurements (thick line) obtained by Hart and August (1988) in comparison to daily aboveground NPP modeled using the Biome-BGC. The vertical axis shows dry matter production (DM) in units of kg ha^{-1} d^{-1}, noting that 1 kg DM is assumed to equal to 0.5 kg C.

This estimate of long-term NPP at the site makes it possible to use the total turnover of C as an additional constraint in the practice of using a time series of measured and modeled ^{14}C values to solve for soil C pool sizes and turnover times. The solution obtained, assuming an active pool turnover rate of 0.5 yr^{-1}, is shown in Figure 2. The parameter values associated with this solution are given in Table 1. This solution does not differ visibly from that presented in Baisden et al. (2013). In contrast to previous work, which assumed steady state and recognized only an stabilized/decadal pool and passive/millennial pool, the work described here has the advantage of recognizing the existence of an active pool with year-to-year dynamics driven by NPP changes.

Introducing an active pool appears to introduce the risk that the model can be underdetermined, meaning that the addition of the 2 parameters (active pool size and turnover rate) cannot be constrained by the data since 4 parameters are already being determined. It is therefore appropriate to examine the sensitivity of the model to different active pool turnover rates, while solving for the size of the active pool. The results from this exercise are shown in Table 2. The sum of squared error values suggest that a range of nearly equivalent best-fit solutions exist with active pool turnover times ranging from ~0.2 to 0.5 yr. Model solutions become unstable for turnover times <0.18 yr and 1.8 yr, with a range of plausible solutions between these values. It is unsurprising that ^{14}C provides little constraint of these short turnover rates, since the resolution of ^{14}C in carbon cycle studies is on the

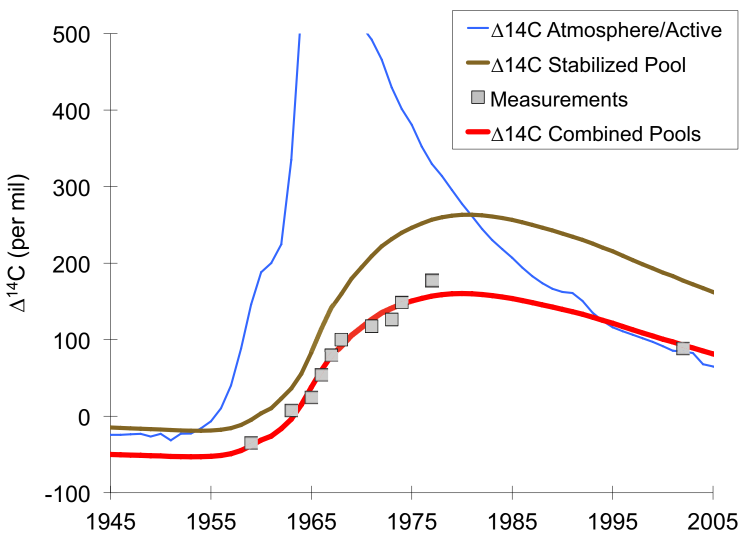

Figure 2 Modeled and measured ^{14}C at the Judgeford site over time. The brown line shows the stabilized pool, and the red line shows the combined active, stabilized, and passive pools. The squares show individual measurements of bulk soil.

Table 1 Pool sizes and turnover times for the model in Figure 1.

Pool	Fraction of total C	kg C m^{-2}	Turnover time (yr)	Turnover (kg C m^{-2} yr^{-1})
Active	0.02	0.4	0.5	0.720
Stabilized	0.73	10.7	20	0.532
Passive	0.25	3.6	1416	0.003
Total	1.00	14.6		1.254

order of 100 yr when variation is driven by radioactive decay and several years to decades when variation is driven by bomb ^{14}C dynamics. The problem of constraining the active pool using NPP also appears to be exacerbated by poor knowledge of belowground NPP, which has not been quantified at the Judgeford site.

To improve the use of ^{14}C in soil carbon cycle studies, it is useful to ask: Does the uncertainty in constraining the active pool undermine the value of bomb ^{14}C in constraining the size and residence time of the stabilized pool that may react to climate change, land use, and other disturbances on decadal timescales that are difficult to study with agricultural or ecological treatment experiments lasting 3 yr? Within the range of solutions in Table 2, it can be seen that the size of the active pool tends to trade-off against its residence time, as do the same size and turnover time of the passive pool. These trade-offs within the range of solutions having similar sum of squared error values suggest that active and passive pool parameters should be treated with some caution. As expected, there is less trade-off in the size and turnover time of the stabilized pool, particularly for active turnover times of 0.2–0.5 yr. Size varies from 0.71 to 0.73 and turnover time from 19.2 to 20.1 yr. Furthermore, the fraction of total soil C turnover (e.g. heterotrophic respiration) derived from stabilized soil C varies only from 0.39 to 0.44 across the full range of solutions. This result emphasizes that time-series ^{14}C measurements constrain model parameters that describe the incorporation and loss of bomb ^{14}C.

Table 2 Best-fit model parameters for a range of different active pool turnover rates. All turnover times are given in years (yr) and fractions are given as a proportion of total soil C. The relative weighting of the sum of squared errors is described in the Methods section.

Active pool turnover time	Stabilized pool turnover time	Passive pool turnover time	Fraction active C	Fraction stabilized C	Fraction passive C	Sum of squared error	Fraction of C turnover from stabilized
0.18	20.0	878	0.010	0.704	0.286	1294	0.39
0.20	19.2	1014	0.010	0.707	0.283	1019	0.42
0.25	19.1	1106	0.012	0.712	0.276	1025	0.43
0.40	19.7	1276	0.020	0.722	0.258	1091	0.43
0.50	20.1	1416	0.025	0.730	0.245	1145	0.42
0.70	20.8	1766	0.035	0.746	0.219	1278	0.42
1.00	22.0	2572	0.050	0.772	0.178	1542	0.41
1.25	23.0	3767	0.062	0.795	0.143	1822	0.41
1.50	23.9	6257	0.074	0.819	0.107	2155	0.41
1.80	25.0	25,562	0.088	0.847	0.066	2623	0.41
2.00	24.8	30,000	0.095	0.838	0.067	2990	0.42
None[a]	17	890	—	0.68	0.32	—	—

[a]Steady-state solution with no active pool from Baisden et al. (2013). For this solution, no data is shown where it is unavailable or not comparable.

It is also worth comparing the results obtained here with those obtained from the steady-state model with no active pool in Baisden et al. (2013). The final row of Table 2 shows that under steady-state conditions, with no active pool, a turnover time of 17 yr was found for the stabilized pool, versus 19–20 yr for the preferred solutions in Table 2. Somewhat surprisingly, introducing an active pool with the model structure used here results in a slight increase in stabilized pool size, with the fraction of total soil C increasing from 0.68 to 0.71–0.73. This is compensated for by decreases in the fraction of passive C, and increases in the residence time of the passive pool. Thus, only small variability and uncertainty is observed to be associated with solutions from different formulations of models used to estimate the flow of bomb ^{14}C through the stabilized pool.

The relatively simple approach of including estimates of NPP with time-series ^{14}C data to further constrain the size and turnover of the pools commonly used to model soil C appears very promising. Similar constraint of soil C dynamics has previously only been achieved through much more complex ^{14}C applications involving depth-dependent transport modeling, density fractionation, and soil respired CO_2 (Gaudinski et al. 2001; Baisden et al. 2002). This method appears widely applicable for grazed pasture, and ecosystems where large stabilized pools with decadal residence times exist. The value of ^{14}C measurements from time-series samples cannot be overemphasized for removing the uncertainty associated with size and turnover of this large stabilized pool from nearly any soil C-cycle study or modeling exercise.

ACKNOWLEDGMENTS

The authors were supported by public research funds through GNS Science (GCT). We gratefully acknowledge the efforts of past researchers to document their work and archive their samples, and a helpful review from K McFarlane.

REFERENCES

Baisden WT, Amundson R. 2003. An analytical approach to ecosystem biogeochemistry modeling. *Ecological Applications* 13(3):649–63.

Baisden WT, Canessa S. 2013. Using 50 years of soil radiocarbon data to identify optimal approaches for estimating soil carbon residence times. *Nuclear Instruments and Methods in Physics Research B* 294:588–92.

Baisden WT, Parfitt RL. 2007. Bomb ^{14}C enrichment indicates decadal C pool in deep soil? *Biogeochemistry* 85(1):59–68.

Baisden WT, Amundson R, Brenner DL, Cook AC, Kendall C, Harden J. 2002. A multi-isotope C and N modeling analysis of soil organic matter turnover and transport as a function of soil depth in a California annual grassland soil chronosequence. *Global Biogeochemical Cycles* 16(4):1135, doi: 1029/2001GB001823.

Baisden WT, Keller ED, Timar L, Smeaton D, Clark A, Ausseil A, Power W, Zhang W. 2010. New Zealand's pasture production in 2020 and 2050. GNS Science Consultancy Report 2010/154. p 1–88.

Baisden WT, Parfitt RL, Ross C, Schipper LA, Canessa S. 2013. Evaluating 50 years of time-series soil radiocarbon data: towards routine calculation of robust C residence times. *Biogeochemistry* 112(1–3):129–37.

Currie K, Brailsford G, Nichol S, Gomez A, Sparks R, Lassey K, Riedel K. 2011. Tropospheric $^{14}CO_2$ at Wellington, New Zealand: the world's longest record. *Biogeochemistry* 104(1):5–22.

Gaudinski JB, Trumbore SE, Davidson EA, Zheng SH. 2001. Soil carbon cycling in a temperate forest: radiocarbon-based estimates of residence times, sequestration rates and partitioning of fluxes. *Biogeochemistry* 52(1):113–4.

Hart PBS, August JA. 1988. Use of nitrogen fertiliser in restoration of pasture productivity and soil fertility after topsoil mining. *New Zealand Journal of Agricultural Research* 31:439–33.

Hart PBS, August JA, West AW. 1989. Long-term consequences of topsoil mining on select biological and physical characteristics of two New Zealand loessial soils under grazed pasture. *Land Degradation and Rehabilitation* 1:77–88.

Jenkinson DS. 1990. The turnover of organic carbon and nitrogen in soil. *Philosophical Transactions Royal Society of London: Biological Sciences* 329(1255):361–8.

Jenkinson DS, Coleman K. 2008. The turnover of organic carbon in subsoils. Part 2 modelling carbon turnover. *European Journal of Soil Science* 59:400–13.

Jenkinson DS, Adams DE, Wild A. 1991. Model estimates of CO_2 emissions from soil in response to global warming. *Nature* 351(6324):304–6.

Keller E, Baisden W, Timar L. 2011. Adapting the Biome-BGC model to New Zealand pastoral agriculture: climate change and land-use change. *AGU Fall Meeting Abstracts*. GC23C-0955.

O'Brien BJ, Stout JD. 1978. Movement and turnover of soil organic matter as indicated by carbon isotope measurements. *Soil Biology and Biochemistry* 10: 309–17.

Parton WJ, Schimel DS, Cole CV, Ojima DS. 1987. Analysis of factors controlling soil organic matter levels in Great Plains grasslands. *Soil Science Society of America Journal* 51(5):1173–9.

Radcliffe JE. 1974. Seasonal distribution of pasture in New Zealand: I. methods of measurement. *New Zealand Journal of Experimental Agriculture* 2:337–40.

Thornton PE, Rosenbloom NA. 2005. Ecosystem model spin-up: estimating steady state conditions in a coupled terrestrial carbon and nitrogen cycle model. *Ecological Modelling* 189(1–2):25–48.

Trumbore S. 2009. Radiocarbon and soil carbon dynamics. *Annual Review of Earth and Planetary Sciences* 37(1):47–66.