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# A Brief Review of the Application of 14C in Terrestrial Carbon Cycle Studies

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An over-arching goal of the DOE TCP program is to understand the mechanistic controls over the fate, transport, and residence time of carbon in the terrestrial biosphere. Many of the modern process and modeling studies focus on seasonal to interannual variability. However, much of the carbon on the landscape and in soils is in separate reservoirs with turnover times that are multi-decadal to millennial. It is the controls on these longer term pools or reservoirs that is a critical unknown in the face of rising GHGs and climate change and uncertainties of the terrestrial biosphere as a future global sink or source of atmospheric $CO_2$ [eg., Friedlingstein *et al*., 2006; Govindasamy *et al*., 2005; Thompson *et al.,* 2004].

Radiocarbon measurements, in combination with other data, can provide insight into, and constraints on, terrestrial carbon cycling. Radiocarbon ($t_{1/2}$ 5730yrs) is produced naturally in the stratosphere when secondary neutrons generated by cosmic rays collide with $^{14}N$ atoms [Libby 1946; Arnold and Libby, 1949]. Upon formation, $^{14}C$ is rapidly oxidized to CO and then to $CO_2$, and is incorporated into the carbon cycle. Due to anthropogenic activities, the amount of $^{14}C$ in the atmosphere doubled in the mid/late 1950s and early 1960s from its preindustrial value of $^{14}C/^{12}C$ ratio of $1.18x10^{-12}$ [*eg.,* Nydal and Lovseth, 1983]. Following the atmospheric weapons test ban in 1963, the $^{14}C/^{12}C$ ratio, has decreased due to the net isotopic exchange between the ocean and terrestrial biosphere [*eg.*, Levin and Hessheimer, 2000] and a dilution effect due to the burning of $^{14}C$-free fossil fuel carbon, the "Suess Effect" [Suess, 1955]. In the carbon cycle literature, radiocarbon measurements are generally reported as $\Delta^{14}C$, which includes a correction for mass dependent fractionation [Stuiver and Polach, 1977].

In the context of carbon cycle studies radiocarbon measurements can be used to determine the 'age' and rate of change of carbon stocks or as a biogeochemical tracer to elucidate processes and pathways. It is this dual nature that can be exploited across scales in space (individual plant, plot or research site, ecosystem, regional, and global) and time (days to millennia). For example, across regional scales, $\Delta^{14}C$ measurements of atmosphere $CO_2$ can be used to attribute carbon dioxide to sources (*e.g*., respiration vs. fossil fuel emissions) or sinks ( *e.g,*. photosynthesis), which cannot be readily inferred from concentration, net flux measurements, or $\delta^{13}CO_2$ [*eg*. Graven *et al.,* 2009; Levin and Hessheimer, 2000; Turnbull *et al.*, 2007]. At smaller scales, similar analyses can be used to elucidate the source, and 'age' of the below ground component undergoing heterotrophic respiration.

Net (biome or ecosystem) uptake of carbon is the difference of two large fluxes: photosynthesis and respiration. Carbon fixation by photosynthesis is, to a large extent, a single process with theoretical underpinnings. On the other-hand, net ecosystem or biome respiration integrates microbial (heterotrophic) and plant (autotrophic) respiration. Eddy covariance methods can be used to estimate bulk $CO_2$ fluxes but they cannot discriminate the process nor the source of the respired $CO_2$. It is these processes that are parameterized in predictive models and contribute to the uncertainty in the climate

forcing effect of the carbon cycle in the future [Friedlingstein *et al*., 2006; Heimann and Reichstein, 2008].

*Radiocarbon measurements to improve our understanding of soil C storage, stabilization, and loss*.

Globally, more C is stored in soils as soil organic matter than in terrestrial vegetation and the atmosphere combined [eg., Schlesinger, 1997; Schurr *et al*., 2007; www.gcp.org]. Soil is the largest single reservoir for carbon stored in the terrestrial system; nearly three quarters of all carbon in the terrestrial reservoir resides in the soil carbon pool including peat and permafrost stores [*eg.*, Schuur *et al.,* 2007]. Soil organic matter is heterogeneous, consisting of components that turn over on timescales ranging from days to thousands of years with input from litter, roots, and other allochtonous detrital components [*e.g*., Davidson *et al*., 1996; Gaudinski 2000; Trumbore 2000; Schuur *et al*., 2001; Swanston *et al.,* 2005]. These sub-pools can be physically separated in the laboratory to determine the distribution of soil carbon amongst labile, intermediate, and stable pools. Radiocarbon measurements for these sub-pools coupled with C stock estimates allow for the calculation of soil organic matter turnover times, which also yield estimates of carbon loss.

Differences in SOM distribution or turnover times amongst sites or over time can indicate factors controlling SOM storage, stabilization, and loss. Terrestrial carbon stocks above- and belowground (in humus and litter layers, woody debris, and mineral soil) are not only sensitive to physical environmental controls (*e.g*., temperature, precipitation, soil moisture) but also to land use history/management, disturbance, "quality" of carbon input (a reflection of plant C allocation and species controls), and the microbial community. The relative importance of these controls on soil C storage and flux can be assessed with radiocarbon-based turnover times and SOM distribution for locations of interest. Information on changes in the rate of exchange between belowground pools are not otherwise discernible: net loss may be determined but the loss could be from a fast or slow turnover pool or the movement of carbon between pools. This information can be coupled with other observations to understand and model the mechanisms for soil organic matter (SOM) protection and the transformation of recently fixed labile carbon into more stable carbon that is sequestered in the biosphere.

*Carbon Allocation and Respiration Partitioning*

Because $^{14}C$ is much more rare than $^{13}C$ (~1:$10^{10}$) radiocarbon can be used as an isotopic tracer in labeling studies using much lower levels of label than the rare stable isotope ($^{13}C$, which is ~1:100 relative to $^{12}C$) [Czimczik *et al*., 2005; Carbone *et al*., 2007]. This allows for the addition of very low amounts of added carbon and for the ability to measure the added label over a wider range of time scales compared to stable isotope labeling techniques which are rapidly diluted. Low-level $^{14}C$ pulse-chase experiments provide valuable information on C cycling patterns across temporal scales ranging from a few hours to months, shorter timescales than can be investigated using C

stock measurements. This type of experiment has been used to study photosynthate allocation patterns [Carbone *et al*., 2007] and determine mean residence time for plant photosynthate in plants [Carbone and Trumbore 2007], to partition ecosystem respiration sources (e.g., plants vs. soil heterotrophs, above- vs. belowground plant tissue) [Carbone *et al*., 2007], and to investigate soil microbial food webs, specifically consumption and subsequent respiration of labile soil organic matter compounds by saprotorphic (decomposer) fungi [Czimczik *et al*., 2005].

'Natural' atmospheric $^{14}CO_2$ can also be used, without an additional tracer or label, to address some of these research questions. Natural abundance can be used to partition total soil respiration, including separation of heterotrophic from root respiration [Czimczik *et al*., 2006] identification of C-sources for microbial decomposition [Czimczik and Trumbore, 2007]. New applications of atmospheric $^{14}CO_2$ levels take advantage of the secular decrease in $\Delta^{14}CO_2$ since ~1963 have been used to determine plant C allocation patterns to explore interannual to decadal stores of non-structural carbon in trees [Czimczik, ICDC8 Jena, DE 2009].

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