Running Head: ForCent Model Development using the Enriched Background Isotope Study

ForCent Model Development and Testing using the Enriched Background Isotope Study Experiment

William J. Parton[1], Paul J. Hanson[2], Chris Swanston[3], Margaret Torn[4], Susan E. Trumbore[5], William Riley[4], Robin Kelly[1]

Corresponding author: William J. Parton

Natural Resource Ecology Laboratory, Colorado State University

Fort Collins, CO 80523-1499

Phone: (970) 491-1987; Fax: (970) 491-1965

E-mail: billp@nrel.colostate.edu

[1] Natural Resource Ecology Laboratory, Colorado State University, Fort Collins, Colorado, USA
[2] Oak Ridge National Laboratory, Oak Ridge, Tennessee, USA
[3] USFS, Northern Research Station, Houghton, Michigan, USA
[4] Lawrence Berkeley National Laboratory, Berkeley, California, USA
[5] School of Physical Sciences, University of California, Irvine, California, USA

Abstract

The ForCent forest ecosystem model was developed by making major revisions to the DayCent model including: 1) adding a humus organic pool, 2) incorporating a detailed root growth model, and 3) including plant phenological growth patterns. Observed plant production and soil respiration data from 1993-2000 were used to demonstrate that the ForCent model could accurately simulate ecosystem carbon dynamics for the Oak Ridge National Laboratory deciduous forest. A comparison of ForCent vs. observed soil pool ^{14}C-signature ($\Delta\,^{14}C$) data from the Enriched Background Isotope Study ^{14}C experiment (1999-2006) shows that the model correctly simulates the temporal dynamics of the ^{14}C label as it moved from the surface litter and roots into the mineral soil organic matter pools. ForCent model validation was performed by comparing the observed Enriched Background Isotope Study experimental data with simulated live and dead root biomass $\Delta\,^{14}C$ data, and with soil respiration $\Delta\,^{14}C$ (mineral soil, humus layer, leaf litter layer, and total soil respiration) data. Results show that the model correctly simulates the impact of the Enriched Background Isotope Study ^{14}C experimental treatments on soil respiration $\Delta\,^{14}C$ values for the different soil organic matter pools. Model results suggest that a two-pool root growth model correctly represents root carbon dynamics and inputs to the soil. The model fitting process and sensitivity analysis exposed uncertainty in our estimates of the fraction of mineral soil in the slow and passive pools, dissolved organic carbon flux out of the litter layer into the mineral soil, and mixing of the humus layer into the mineral soil layer.

Index Terms: 0400 Biogeosciences; 0428 Carbon cycling (4806); 0439 Ecosystems, structure and dynamics (4815); 0466 Modeling (1952); 0486 Soils/pedology (1865)

Key Words: Modeling, Soil carbon, Soil $\Delta^{14}C$, Litter decomposition, Century, ForCent

1. Introduction

Decomposition of root and leaf litter is a critical process for releasing soil nutrients for plant growth and for providing substrate for the formation of soil organic matter. This process is included in all of the major ecosystem models [see Century: *Parton et al.*, 1987; Biome-BGC: *Running and Coughlan*, 1988; DNDC: *Li et al.*, 1994; Roth-C: *Coleman and Jenkinson,* 1996]. Root and leaf litter substrate is incorporated into soil organic matter pools with rapid, intermediate, and slow turnover times. The conceptual development of these pools was based on studies of the impact of root and leaf litter decay on soil organic matter levels and nutrient dynamics [*Meentemeyer*, 1978; *Melillo et al*., 1982; *Hobbie*, 1996; *Parton et al*., 2007a].

The most common technique for studying these decomposition dynamics is to use litter bags [reviewed in *Wieder and Lang*, 1982; *Parton et al.*, 2007a]. Most litter bag studies have been run for relatively short time periods [three years or less: *Shanks and Olson*, 1961; *Lousier and Parkinson*, 1976; *McClaugherty et al*., 1985; *Aerts et al*., 2003]; however, a few studies were run for a longer period time (five or more years: *Trofymow et al*., 2002; *Parton et al*., 2007a). Results from the long-term studies suggest that 5-20% of the initial litter plant biomass is stabilized into the slow turnover soil organic matter pool. The recent global litter decay study by Parton et al., (2007a) showed photodegradation can greatly enhance surface litter decay rates for dry grassland ecosystems; however, photodegradation does not seem to be an important process for humid grasslands and forest ecosystems. The major limitation of litter bag techniques, however, is that

they do not directly evaluate the subsequent fate of nutrients and organic matter released from litter bags [see *Dornbush et al*., 2002].

A number of studies using isotopic tracers (^{13}C and ^{14}C) have been conducted to address gaps in the scientific knowledge of the relationships between litter decomposition and the formation of soil organic matter [*Jenkinson*, 1971; *Wang et al*., 1996]. Since the isotopic signature of soil organic matter is similar to the vegetation system under which it was formed, a difference in plant vs. soil $\Delta\ ^{13}C$ suggests a relatively recent change in plant cover. Isotopic approaches have been used to track changes in ecotone boundaries [*Steuter et al*., 1990; *McClaran and McPherson*, 1995], detect land use conversion from tropical C_3-dominated forests to C_4-dominated cropping systems [*Osher et al*., 2003]. Estimates of the minimum age of a soil organic matter pool or the mean residence time of the organic material are possible using ^{14}C-dating [*Paul et al*., 1997], and may be used to track changes in slow and passive soil organic matter. Both ^{13}C- and ^{14}C-signatures ($\Delta\ ^{13}C$ and $\Delta\ ^{14}C$, respectively) are used to track litter decomposition and soil organic matter formation and stabilization [*Follett et al*., 2007]. The results from these studies support the three-pool soil organic matter structure common in ecosystem soil C cycle models.

This paper describes the use of the Enriched Background Isotope Study $\Delta\ ^{14}C$ [*Hanson et al*., 2005] litter and root experiments to calibrate, develop, and test a mechanistically improved forest version of the DayCent model (ForCent). The main objective of this paper is to determine how well the extensive Enriched Background Isotope Study $\Delta\ ^{14}C$ data sets can be used to determine the turnover rates of the different soil organic matter pools using a process-based ecosystem model. We utilized the classic modeling approach by using part of the observed data to develop the new model and then selected a segment of the observed data to perform a true model

validation. A detailed description of the new ForCent model, the procedure used to calibrate the model, limitations of the ForCent model, and a comparison of the model results with the observed data sets are also presented. In addition, we included a sensitivity analysis of the model to the assumed atmospheric $\Delta^{14}C$ values and the fraction of mineral soil carbon in slow and passive fractions.

The ForCent model described here is better poised to address outstanding issues in the terrestrial carbon cycle, including: (1) the partitioning of soil carbon turnover between autotrophic and heterotrophic sources, (2) the partitioning of heterotrophic respiration sources between above-ground litter decomposition and below-ground root detritus decomposition, and (3) the clarification of pathways leading from leaf and root detritus to long-term stabilization of soil organic matter. By incorporating a new understanding of important forest carbon cycling pools and processes, ForCent is better prepared to address questions such as the influence of climatic change on the longevity of new carbon additions to soils and the fate of long-lived storage pools through time.

2. Methods

2.1. The Enriched Background Isotope Study

The Enriched Background Isotope Study project [*Trumbore et al*., 2002; *Hanson et al*., 2005; *Swanston et al*., 2005] started in the fall of 2000 on the U.S. Department of Energy's National Environmental Research Park near Oak Ridge, Tennessee. The Enriched Background Isotope Study plots are located on ridge-top and up-slope positions which are dominated by oak forests that range in age from 65 to 150 years. Available aerial photographs show that the Enriched Background Isotope Study sites are located on the east branch of the watershed which had a

105 closed canopy forest cover in 1935. The exact date for a prior clear-cut disturbance for the
106 Enriched Background Isotope Study plots is not exactly known; however, the state of the forest
107 in 1935 suggests that forest regrowth started after a 1900 clear cut. The experimental sites
108 included two soil types and two levels of ^{14}C exposure in 1999. Reciprocal transplants of
109 enriched vs. near-background litter were established on sites that had large (western site) and
110 minimal (east site) exposure to enhanced atmospheric levels of ^{14}C in 1999. Enriched ^{14}C leaf
111 litter was collected from the western site during the fall of 2000, while background ^{14}C litter was
112 collected from the eastern site during the same time period. Near background and enriched ^{14}C
113 leaf litter were added to the plots in May 2001, with continued additions of elevated and ambient
114 leaf litter (during winter months) for the next two years. Plots in the replicated experimental
115 design included those with: 1) ^{14}C enriched soil carbon, root litter, and leaf litter; 2) ^{14}C enriched
116 roots, soil carbon, and near background leaf litter; 3) near-background roots, soil carbon, and
117 elevated ^{14}C leaf litter; and 4) near background leaf litter, roots, and soil carbon. The ^{14}C content
118 of surface litter, humus, mineral soil layers, and soil respiration rates were measured from 2001
119 to 2005. As of 2004, natural background ^{14}C leaf litter was allowed to fall into the treatment
120 plots.

121 Atmospheric ^{14}C levels elevated during the aboveground testing of nuclear weapons have
122 been used as a tracer for the interpretation of biological carbon pathways for many years;
123 however, that tracer is now returning to pre-bomb levels limiting the sensitivity of such
124 observations [*Swanston et al.,* 2005]. The local and unexpected enrichment of background ^{14}C on
125 the Oak Ridge Reservation provided a unique opportunity to address soil carbon cycling at
126 annual and even sub-annual time scales allowing for the direct testing of soil carbon cycle

mechanisms in forests at previously unresolved time intervals [*Trumbore et al.,* 2002; *Froberg et al.,* 2007].

2.2. DayCent Model Description

The DayCent model [*Kelly et al*., 2000; *DelGrosso et al*., 2001a, 2001b; *Parton et al*., 2001] is the daily version of the Century model [*Parton et al*., 1987] developed to simulate daily trace gas fluxes (CO_2, N_2O, NOx, CH_4, N_2) from ecosystems. The objective was to develop a model capable of simulating full greenhouse gas fluxes and net ecosystem exchange of carbon for agricultural systems, grasslands, savanna, and forest systems. The model has been used extensively to simulate the ecosystem dynamics of grasslands and forest and cropping systems in the U.S. [*Kelly et al*., 2000; *DelGrosso et al*., 2001a; *DelGrosso et al*., 2005]. *DelGrosso et al*. [2005] recently used the DayCent model to simulate the impact of agricultural management practices on soil carbon levels, trace gas fluxes, and crop yields for agricultural systems in the U.S. at site, regional, and national levels. The DayCent model has also been used to simulate the impact of nitrogen deposition, changing CO_2 levels, and future climatic changes [*Pepper et al*., 2005; *Parton et al*., 2007b; *Luo et al*., 2008] on grassland and forest systems. The model simulates soil nutrients (N and P) and carbon dynamics, trace gas fluxes (N_2O, NOx, N_2, and CH_4), plant production and nutrient uptake, and soil water and temperature dynamics (Figure 1). The DayCent model uses a daily time step to simulate trace gas fluxes and soil nutrient and carbon dynamics, one half hour time for the soil water flow, and daily time step for the plant production submodel.

The plant production submodel simulates the growth of forests, grasslands, and savanna systems. Important processes represented in the plant growth submodel include plant death, plant

150 phenology, uptake of soil nutrients, and growth of different plant parts. The factors controlling
151 plant growth are daily solar radiation, soil water and temperature, live leaf area, and soil nutrient
152 uptake by plants. A detailed description of the plant growth submodel is presented by *Kelly et al*.
153 [2000] and *DelGrosso et al*. [2001a]. The plant growth model simulates dynamic allocation of
154 carbon to the different plant parts as a function of water and nutrient stress. This paper presents a
155 detailed description of the most recent changes to the forest plant growth submodel.
156 The soil temperature and water submodels simulate daily soil temperature and water content
157 for the soil layers represented in the model. The soil temperature model is described by *Eitzinger*
158 *et al*. [2000], while *Parton et al*. [1998] present a detailed description of the soil water model.
159 The soil water model simulates saturated and unsaturated water flow, surface runoff, and deep
160 drainage below the plant rooting zone. Darcy water flow equations are used to simulate water
161 flow between soil layers using a one-half hour time step. Anaerobic conditions resulting from
162 snow melt into frozen soil layers are represented in the model. Soil temperatures are simulated
163 for each 5 cm depth increment using an analytical solution to the soil heat flow equations. The
164 soil temperature and water models have been tested extensively [*Frolking et al*., 1998; *Eitzinger*
165 *et al*., 2000; *DelGrosso et al*., 2001a].
166

167 **2.3. ForCent model changes**

168 The major changes to the ForCent model include: 1) adding a surface litter slow organic
169 matter pool (humus layer); 2) altering the surface litter decay submodel; 3) adding the *Parton et*
170 *al*. [1978] root growth model; 4) adding a plant stored carbohydrate pool, and 5) including the
171 impact of phenology on seasonal plant growth patterns. The ForCent model divided the slow
172 pool into a surface slow pool (humus) and a mineral soil slow pool (see Figure 2). The need for

this change was emphasized by *Kelly et al*. [1997]. As part of this change, we added a flow that simulates the physical mixing of the humus layer into the soil mineral slow pool. The surface litter layer corresponds to the sum of the Century surface litter pools (structural and metabolic pools) and the surface microbial biomass pool.

The *Riley et al*. [2009-Radix 1.0] and *Parton et al*. [1978] root growth models assume that live fine roots are composed of roots with fast and slow turnover rates. The roots with fast turnover rates are called juvenile roots, and roots with slow turnover rates are called mature roots. *Riley et al*. [2009] suggest that juvenile roots have turnover times < 1.0 year, while mature roots have turnover times > 10.0 years. The ForCent model has incorporated a revised version of the *Parton et al*. [1978] root growth model (Figure 3). The main structural change for the ForCent root model was to combine the juvenile and non-suberized roots into juvenile roots, and then refer to the suberized roots as mature roots. The major process included in the *Parton et al*. [1978] model includes maintenance respiration, growth of new roots, aging of juvenile roots, and root death. Root maintenance respiration and root death are calculated as a function of soil water content of the wettest layer and soil temperature, while aging of roots is a function of soil temperature. The impacts of soil water and temperature on these processes are represented using the *Parton et al*. [1978] model, while the maximum rates for root aging and root death were parameterized based on the live root biomass data from the Enriched Background Isotope Study [*Joslin et al*. 2006].

The revised model uses the original Century equations [*Parton et al*., 1987] to control litter decay for the soil pools (structural and metabolic dead roots, soil microbial biomass, and slow and passive soil organic matter) within the mineral soil layer. Surface litter decay rates are now a

195 function of time since rainfall, average soil surface temperature, and soil water content of the 0-4
196 cm soil layer using equation 1:

197 $$Di = Ki * Bi * R * F(Ts) * F(w) \quad (1)$$

198 where Di is the decomposition rate (g C m^{-2} d^{-1}) of ith soil pool (I = 1, 2, 3, and 4 for the surface
199 metabolic, structural, microbial and humus pools), Ki is the maximum decay rate (d^{-1}) for the ith
200 surface litter pool, Bi is the carbon level (g C m^{-2}) in the ith surface litter pool, R is the rainfall
201 event multiplier (set equal to 1.0 for no precipitation days and 3.0 for days when precipitation is
202 > 10.0 mm), F (Ts) is the impact of temperature on decomposition (Figure 4a), and F (w) is the
203 effect of soil water on litter decay (Figure 4b). The same temperature and water functions are
204 used to simulate decay rates for the soil mineral pools (R is not used for the mineral soil pools).
205 Continuous soil respiration data from the Oak Ridge National Laboratory [*Hanson et al*., 2005]
206 show that soil respiration rates from the surface litter increase rapidly following rainfall events
207 and then decrease as the soil litter dries out (generally within 24 to 36 hours).

208 The ForCent model includes a stored carbohydrate pool and currently assumes that gross
209 photosynthesis is equal to two times the net plant growth rates [*Waring et al*., 1998; *DeLucia et*
210 *al.*, 2007; *Litton et al*., 2007]. It predicts potential net plant growth rates as a function of air
211 temperature, water stress, and light interception, and then reduces these rates if nutrients are not
212 available. Stored carbohydrate is used to support growth of new leaves in the spring, with 50% of
213 new leaf growth coming from this pool. Carbon in the stored carbohydrate pool is the source for
214 growth and maintenance respiration. The model assumes that growth respiration is equal to
215 23.3% of the total growth of the different plant parts [*Hanson et al*., 2003a], while maintenance
216 respiration rates are calculated using a model developed by *Ryan et al*. [1995] for live leaves,
217 branches, coarse roots, and stems. The Ryan respiration model assumes that each plant part has a

specific respiration rate and uses an exponential function to represent the effect of temperature on maintenance respiration (Q_{10} = 2.0). The ForCent model assumes that maintenance respiration rates are decreased if the carbohydrate pool is less than two times the maximum leaf carbon level. We also assume that the stored carbohydrate pool will not exceed five times the maximum leaf carbon level (carbon inputs to the stored carbohydrate are set equal to zero if the maximum level is exceeded). The assumption regarding the maximum level for stored carbohydrate pools is based on the concept that photosynthesis rates decrease if plant carbohydrate levels are too high, while low levels of stored carbohydrates reduce maintenance respiration.

The ForCent model includes a dynamic carbon allocation scheme which assumes that fine root growth has first priority, followed by live leaves and wood growth. The plant growth model calculates the maximum plant growth rate as a function of air temperature, intercepted solar radiation, and water stress [*Parton et al*., 2001]. The model calculates the fraction of plant production going to fine root growth (Fr) as a function of the water and nutrient stress using equation 2:

$$Fr = \text{maximum}\,(F\,(Ws), F\,(Ns)) \qquad (2)$$

where F (Ws) is the impact of water stress on Fr (increases linearly from 0.05 to 0.18 as water stress increases from the minimum value to the maximum value) and F (Ns) is the impact of nutrient stress on Fr (increases linearly from 0.05 to 0.18 as nutrient stress increases from the minimum value to the maximum value). The ratio of available nitrogen to plant nitrogen demand is used as the index for nutrient stress (ratio equal to one is associated with minimum nutrient stress), while the water stress term comes from the plant growth model. Fine root growth occurs during the time periods when net plant production is positive and during the first month of spring leaf out using the stored carbohydrate pool.

241 Live leaf growth receives the remaining carbon and nutrients available for plant growth until
242 the maximum live leaf area is attained. Maximum leaf area is specified for each plant type as a
243 function of the aboveground wood biomass using an allometric function. Wood growth occurs
244 after maximum leaf area is attained using the remaining available carbon and nutrients for wood
245 growth. The model specifies the fraction of carbon promoting wood growth in various plant parts
246 (20%, 65%, and 15% respectively for fine branches, large wood and coarse roots). Wood growth
247 is assumed to occur during the first four months following spring leaf out. The plant phenology
248 rules are based on Oak Ridge site data showing that maximum leaf area is attained a month after
249 spring leaf out starts and that new wood growth starts after maximum leaf area is attained, but
250 before the end of July. Initiation of spring leaf out starts after the weekly running average air
251 temperature exceeds 10° C and leaf senescence occurs after the weekly running average air
252 temperature drops below 7° C.
253

254 **2.4. The Enriched Background Isotope Study Computer Runs**

255 The ForCent model was set up to simulate the Enriched Background Isotope Study
256 experiments by running the model to equilibrium conditions using a 1900-year computer
257 simulation that used observed daily weather data (1900-2005) and soil texture data as inputs to
258 the model. In 1900, the forest was clear cut and then started to re-grow. The ecosystem dynamics
259 from 1900 to the present were simulated using the observed weather data from that time period.
260 The Enriched Background Isotope Study model experiments for the east and west sites were
261 started in 1995. The atmospheric $\Delta\ ^{14}C$ levels taken from 1950 to 2005 (Figure 4c) show that
262 they started to increase in the mid 1950s, peaked in the late 1960s, and have decreased since
263 then. Locally, elevated atmospheric $\Delta\ ^{14}C$ levels started to increase in 1995 for the west Enriched

Background Isotope Study site, but did not start to increase until 1999 for the east site. These atmospheric $\Delta\ ^{14}C$ values were assumed to be 0.0 before 1950. After 1995, the atmospheric $\Delta\ ^{14}C$ values for the east and west sites were assumed to be equal to the observed yearly average of new wood cellulose $\Delta\ ^{14}C$ values.

The Enriched Background Isotope Study experiments were set up using four different model runs where low and high $\Delta\ ^{14}C$ labeled leaves were added to both the east and west sites. We simulated the exclusion of ambient senescing leaves in the fall of 2000, 2001, and 2002 at all of the sites, and then simulated their replacement by the addition of fixed masses of ambient and high $\Delta\ ^{14}C$ labeled leaves in May of 2001, and January of 2002 and 2003. The west site had enriched $\Delta\ ^{14}C$ roots and soil C because of the elevated atmospheric $\Delta\ ^{14}C$ levels, while the east site had background $\Delta\ ^{14}C$ roots and soil C levels because of lower atmospheric $\Delta\ ^{14}C$ levels (Figure 4c).

2.5. ForCent Model Calibration

The data sets used to calibrate the parameters of the ForCent model include the observed plant production data (by biomass pool) at the Oak Ridge National Laboratory from 1993 to 2000 [*Hanson et al*., 2003a], soil respiration data from 1993 to 2000 [*Hanson et al*., 2003b], and the observed Enriched Background Isotope Study soil carbon $\Delta\ ^{14}C$ data from 2000 to 2005 for the surface litter, humus, and mineral soil layers (0-30 cm depth). We used a two-step process to calibrate the ForCent model. The first step was to use the observed plant production and biomass data from the Oak Ridge site to determine parameters in the plant production submodel. Most of the plant production submodel parameters were estimated based on direct observations from this site. The observed plant production and ecosystem carbon levels of the major plant parts

[*Hanson et al*., 2003b] were used to determine the maximum live leaf area, turnover rates, and allocation of carbon to the live fine root, branch, leaf, large wood, and coarse root pools. The maximum maintenance respiration rates are 3.4 y^{-1} and 3.1 y^{-1} for juvenile and mature roots, and were adjusted to match the total soil respiration rates observed at the Oak Ridge National Laboratory site [*Hanson et al*., 2003b]. The key assumption used for adjusting maintenance respiration rates is that modeled heterotrophic respiration rates have greater certainty compared to root maintenance respiration values. Maximum root death rates are 9.6 y^{-1} and 2.2 y^{-1} for juvenile roots and mature roots are parameterized so that total fine root biomass matched the *Joslin et al*. [2006] data set. This data set was also used to derive the fraction of carbon allocated to root growth in the mineral soil and humus layers (95% and 5% respectively), the maximum fraction of juvenile roots transferred to mature roots (1.5 y^{-1}), and the fraction of new root growth allocated to juvenile roots (95%) and mature roots (5%). Growth respiration rate is assumed to be 23.3% for all of the live plant parts [*Hanson et al*., 2003b]. The relative difference among the maximum maintenance respiration rates for live leaves, fine branches, large wood, and coarse roots was based on data from *Ryan et al.* [1996] showing that live leaves have the highest respiration rates and that wood respiration rates are more than one order of magnitude lower than live leaf respiration rates. Ecosystem nitrogen inputs were adjusted so that the observed mean annual production matched the observed data.

The second step in the model calibration process was to use the observed time series (1972-2004) of $\Delta\ ^{14}C$ data for the mineral soil and humus layers to determine the mixing rate of humus material into the mineral soil layer, the maximum decay rates for the humus layer, and the soil mineral slow pool and passive soil organic matter pools. The model fitting process showed that the site specific best fit to mineral soil $\Delta\ ^{14}C$ was to have 40% of the mineral soil organic matter

in the slow pool for the west site and 55% for the east site. We used maximum turnover rates for the slow and passive soil organic matter so that 47% of the total soil organic matter was slow material in order to best fit the combined east and west mineral soil $\Delta\ ^{14}C$ data. The maximum turnover rate of the humus, mineral slow pools, and soil passive pools, and mixing of the humus slow pool into the mineral soil layer, was estimated by finding parameters that resulted in the best fit (minimum root mean square error) to the observed soil and litter layer $\Delta\ ^{14}C$ data. There is more uncertainty in these parameters since the observed soil $\Delta\ ^{14}C$ data didn't include direct measures of the turnover rates for the different soil organic matter pools.

Appendix 1 presents a list of the parameter values, including the definitions of the model parameters which were adjusted to best fit observed data from the Oak Ridge site. Numerous documents containing the information needed to reproduce the model results shown here, such as the version of the ForCent model used in this paper, the computer code, user manuals, definitions of all of the model parameters, guides on how to use the model, and weather data sets used to run the model, can be downloaded from the following web site: (http://www.nrel.colostate.edu/projects/daycent/downloads.html).

3.0. Results

3.1. ForCent Model Verification

From 1993 to 2000, model results compare favorably with observed mean plant production (Table 1). Both the model and the data show that leaf production does not vary substantially between years, while there are considerable year-to-year changes in fine root and wood plant production. The absolute mean error of annual leaf and total plant production are less than 10% of the mean annual production (6% and 9%), while absolute mean error for wood production and

fine root production are less than 20% of mean annual production (17% and 15%). Year-to-year variability in live leaf, wood, and total production are reasonably well simulated with r^2 values greater than 0.50 (r^2 = 0.61, 0.60, and 0.53); however, yearly changes in fine root production are not as well simulated with r^2 for fine roots less than 0.40. A comparison of the current ForCent simulated annual plant production with results from earlier versions of the DayCent model show that the ForCent model does a better job of simulating year-to-year changes in annual plant production (earlier DayCent model had an r^2 = 0.15 and absolute mean error of 181 gm C m^{-2} y^{-1} for total plant production vs. r^2 = 0.53 and absolute mean error of 55.0 ForCent).

Hanson et al. [2003b] developed a data-based soil respiration model for predicting daily soil respiration at the Oak Ridge National Laboratory site. The mean and range of the annual soil respiration from 1993 to 2000 for the Hanson and ForCent models (Table 1) are quite similar, the r^2 for the ForCent and Hanson model comparison for annual soil respiration is quite high (r^2 = 0.77), and the absolute mean error between the two models is less than 6% of the mean annual soil respiration rate. A comparison of the Hanson and ForCent simulated daily soil respiration results from the 1993 to 2000 shows that the results are quite similar for six years (r^2 range from 0.62 to 0.84), while during two of those years (1998 and 1999), the comparisons are less favorable (r^2 < 0.50). Periods when the models do not agree occur when the ForCent model simulates lower soil respiration rates because of lower than normal juvenile root biomass and root production. Unfortunately, the limited observed daily soil respiration during those two years doesn't allow us to determine which model is more accurate. A comparison of the ForCent model predictions of daily soil respiration with the previous forest DayCent model underestimated soil respiration on days with precipitation which resulted in a 50% to 100% underestimate of soil respiration when observed respiration is > 4 g C $m^{-2}d^{-1}$.

Patterns for $\Delta^{14}C$ of the surface litter, humus, and the 0-30 cm mineral layers for the enriched and near-background litter addition treatments (Figures 5 and 6; Table 2) show a general agreement between the model results and observed data. The model and data show that the $\Delta^{14}C$ content of the surface litter layer (Figure 5) is higher for the west site compared to the east site, and that the near-background litter treatment has lower $\Delta^{14}C$ content compared to the enriched treatment. The overall fit of the model to the observed data is similar for both the east and west sites, and the mean absolute error (Table 2) ranges from 27 gm C m^{-2} for the east site low treatment to 52 gm C m^{-2} for the west site low treatment. The higher surface litter $\Delta^{14}C$ content of the west site compared to the east site reflects the higher atmospheric $\Delta^{14}C$ content of the west site (Figure 4a).

A comparison of observed and simulated $\Delta^{14}C$ of the humus layer (Figure 5c,d) shows increased $\Delta^{14}C$ levels for enriched litter additions. The ForCent simulations for the west site capture the $\Delta^{14}C$ increase of the humus layer beginning in 1999, following the large atmospheric $\Delta^{14}C$ exposures (see Figure 4a). This contrasts with the simulated humus $\Delta^{14}C$ levels in the east site which decrease until 2000, and then stabilize around 190‰ for ambient plots with near-background litter additions. The model results compare well, yet the results from the east site are more consistent with fewer discrepancies. The absolute mean errors are much lower for the high and low treatments for the east site (21 and 8 gm C m^{-2}) compared to the west site (53 and 85 gm C m^{-2}). This pattern of better fit of the model to observed data from the east site is true for both the humus layer and the surface litter layer. The major discrepancy for the humus layer is an underestimate of the west site $\Delta^{14}C$ value for 2001. It was impossible to adjust the maximum turnover rate of the humus layer to fit both the 2001 point and the observations from 2002 to 2005.

379 A comparison of the observed and simulated soil mineral $\Delta^{14}C$ (0-30 cm soil depth) values
380 from 1950 to 2005 (Figure 6a) for the low east site shows that the soil $\Delta^{14}C$ values peaked from
381 1975 to 1985, and then started to decrease. The major discrepancy is the model underestimate of
382 the soil $\Delta^{14}C$ in 1973 which is likely a result from the fact that the observed 1973 $\Delta^{14}C$ value is
383 for the 0-15 cm depth (simulated 0-30 cm depth soil includes older soil that has not been
384 impacted by the recent increases in atmospheric $\Delta^{14}C$ bomb carbon). Model results for the east
385 site show a continuing pattern of decreasing $\Delta^{14}C$ values for both litter addition treatments from
386 1995 to 2005 (Figure 6b). This contrasts with the west site results after 1999 where increases in
387 soil $\Delta^{14}C$ are observed and simulated (Figure 6b). The observed data is consistent with
388 simulations showing higher soil $\Delta^{14}C$ values for the west site compared to the east site, and
389 higher values of $\Delta^{14}C$ by 2005 for the enriched litter treatment. The observed vs. simulated mean
390 absolute error for the mineral soil $\Delta^{14}C$ values in the high and low treatments in the west site is
391 lower (10 and 8 gm C m^{-2}) compared to the east site (12 and 14 gm C m^{-2}). The biggest model
392 discrepancy is an underestimate of the east site low treatment humus $\Delta^{14}C$. The standard
393 deviation for the observed mineral soil $\Delta^{14}C$ data is quite high for both sites.
394

395 **3.2. Model Validation Comparisons**

396 The Enriched Background Isotope Study soil respiration $\Delta^{14}C$ data for the mineral soil,
397 humus, and surface litter layers, and for total soil respiration, along with the dead and live root Δ
398 ^{14}C data, were not used in the model calibration process, and as a result, could be used to validate
399 model predictions. A comparison of the observed vs. simulated $\Delta^{14}C$ values for the live and
400 dead roots for the east and west sites (Figure 7) generally agree with higher $\Delta^{14}C$ values for the
401 dead and live roots in the west site, and a pattern of decreasing $\Delta^{14}C$ values from 1999 until

2004 for both sites. The elevated $\Delta\ ^{14}C$ values after 2004 are due to increased atmospheric $\Delta\ ^{14}C$ for both the east and west sites (higher increases in the west site). A comparison of the simulated live juvenile root $\Delta\ ^{14}C$ values with the new root growth screen data (Figure 7c - root biomass that grows in screens inserted into the soil) shows that the model correctly predicts the observed decreases in $\Delta\ ^{14}C$ values following the 1999 atmospheric labeling events; higher $\Delta\ ^{14}C$ values for the west site compared to the east site, and the observed increase in $\Delta\ ^{14}C$ values in 2004 and 2005. The major discrepancy is an overestimate of live (total root biomass and juvenile roots) and dead root $\Delta\ ^{14}C$ values by the model for the west site from 2001 to 2004.

Simulated total soil respiration and $\Delta\ ^{14}C$ values for the west site during August 2003 (Figure 8) show large day-to-day changes in total soil respiration and spikes in the $\Delta\ ^{14}C$ values for the high ^{14}C litter treatments associated with rainfall events. These results are consistent with the data from *Cisneros-Dozal et al*. [2007] showing a 50-100% increase in soil respiration $\Delta\ ^{14}C$ values following rainfall events for the high treatments and minimal changes in $\Delta\ ^{14}C$ of soil respiration following rainfall events for the low treatments. Increases in the $\Delta\ ^{14}C$ of soil respiration following rainfall events for the high treatments are caused by rainfall-induced increased decomposition of the highly labeled surface litter layer (surface litter and humus layers).

A comparison of the observed vs. simulated $\Delta\ ^{14}C$ soil respiration values for all of the soil pools and different treatments (Figure 9) shows that the model performed well, representing the observed data set ($r^2 = 0.75$). Simulated mean mineral soil respiration $\Delta\ ^{14}C$ values (Figure 9a) follow a pattern of higher $\Delta\ ^{14}C$ levels in the east site; however, the model tends to underestimate the observed increase in $\Delta\ ^{14}C$ levels for the high vs. low treatments at both the east and west sites. Our results suggest that the model underestimated the amount of labeled aboveground litter

dissolved organic carbon transported to the mineral soil layer, and lost as soil respiration from the mineral soil layer. Simulated and observed 2001 soil respiration $\Delta\ ^{14}C$ values for the surface litter and humus layers (Figure 9b) follow the general pattern of higher values for the west site, and an increase in $\Delta\ ^{14}C$ levels with the high treatment. The model tends to underestimate the humus layer $\Delta\ ^{14}C$ content and also appears to be underestimating the amount of the elevated $\Delta\ ^{14}C$ material that is transferred to the humus layer for the west site.

3.3. Sensitivity Analysis

The model tuning process revealed that results are sensitive to the assumed values of the atmospheric $\Delta\ ^{14}C$ values on the east and west sites, and also to the fraction of the mineral soil organic matter in the passive pool (Figure 1). We assumed that the atmospheric $\Delta\ ^{14}C$ values for the east and west sites were equal to the observed $\Delta\ ^{14}C$ values of new wood cellulose. Observed atmospheric $\Delta\ ^{14}C$ values for the east and west sites were measured from 2001 to 2005, showing variability both within the year and among different years. The impact of changing the atmospheric $\Delta\ ^{14}C$ values by ± 30% after 1995 on simulated mineral soil $\Delta\ ^{14}C$ values (Figure 10a,b) shows that the model best fit the west site observed soil $\Delta\ ^{14}C$ values for the high and low treatments with a 30% increase in atmospheric $\Delta\ ^{14}C$ levels. Similar results are also found for the simulated $\Delta\ ^{14}C$ values for the humus layer (data not presented) in the high and low treatment model runs for the west site, thus suggesting that the mean atmospheric $\Delta\ ^{14}C$ values were underestimated by the cellulose $\Delta\ ^{14}C$ values in the west site. Unfortunately, model results for the simulated live and dead roots in the east site don't agree with these results since elevating the atmospheric $\Delta\ ^{14}C$ values by 30% increased the simulated overestimate of the live and dead root

447 $\Delta\ ^{14}C$ values (data not shown). Results for the east site (Figure 10c,d) show that the best model
448 results for the mineral soil $\Delta\ ^{14}C$ values occur with a 30% reduction in atmospheric $\Delta\ ^{14}C$ values.
449 The best fit estimate of the fraction of mineral soil organic matter in the passive fraction for
450 combined east and west sites was 47%. We kept the total mineral soil organic matter fixed and
451 altered the decay rates of slow and passive pools in order to set up computer model runs with
452 40% and 55% passive soil organic matter. Results for the east site (Figure 11a,b) showed that the
453 best fit to the observed mineral soil $\Delta\ ^{14}C$ data was obtained with 55% passive soil organic
454 matter. The improved fit to the observed data was clearest for the east site low treatment where
455 the model overestimated the observed soil $\Delta\ ^{14}C$ values. Opposite results were observed for the
456 west site where the 40% passive run was best fit to the observed high and low mineral soil $\Delta\ ^{14}C$
457 values.
458

459 **4. Discussion**

460 We demonstrate here that the ForCent model can successfully simulate carbon dynamics of
461 deciduous forest systems. Model results were compared with observed plant production data,
462 carbon in the soil and plant pools, and $\Delta\ ^{14}C$ dynamics for plants and soils during the Enriched
463 Background Isotope Study experiment. Data from the Oak Ridge National Laboratory site was
464 used to make major changes to the ForCent model and calibrate some of the parameters. The
465 major improvements in the model include adding a detailed root growth model, a dynamic plant
466 carbon allocation scheme, a surface humus layer, plant phenology in the plant production
467 submodel, including a rainfall pulse response to the surface litter decay, and adding a plant
468 stored carbohydrate pool. A comparison of the earlier DayCent model results show that the new
469 ForCent model greatly improved the ability of the model to simulate year to year changes in

forest plant production (total plant production r^2 increased from 0.19 to 0.52). The process of adding plant phenology and seasonal patterns in wood growth (wood growth ceases at the end of July) resulted in a decrease in the simulated inter-annual variability of plant production, consistent with the observed inter-annual production data [*Hanson et al*., 2003a]. Stopping wood growth at the end of July results in plant storage of soil nutrients from August to October, and then utilized during the next growing season.

One of the major improvements in the ForCent model was to include the precipitation pulse event multiplier for the surface litter decay based on the *Hanson et al*. [2003a] data-based soil respiration model. Comparison of the Hanson- and ForCent-simulated daily soil respiration rates, taken from 1993 to 2000 for the Oak Ridge National Laboratory site, showed close agreement with the observed data for both models (r^2 = 0.61 and 0.64). Comparison of the daily simulated soil respiration for the Hanson and ForCent models for six of the eight years was quite good (r^2 ranging from 0.72 to 0.84). The ForCent model predicted lower soil respiration compared to the Hanson model during two of the years when ForCent predicted lower than average live root biomass and root production. Lower total soil respiration simulated by ForCent during these time periods resulted from reduced autotrophic respiration (maintenance plus growth) from the live roots. Root dynamics in the ForCent model are quite dynamic and respond to year-to-year differences in plant production and water stress, while the Hanson model assumed root growth patterns were less dynamic. It is not clear which model is correct since we did not have sufficient observed data during the time periods when the major ForCent and Hanson model differences were observed.

The ForCent model correctly simulated higher $\Delta\ ^{14}C$ levels for the surface litter and mineral soil pools in the west site, higher $\Delta\ ^{14}C$ levels for the high labeled litter treatment, and also the

493 incorporation of highly labeled leaf litter into the humus layer. Simulated results for the west site
494 showed lower $\Delta\ ^{14}C$ levels for mineral soil and humus layers compared to the observed data and
495 suggest that the atmospheric $\Delta\ ^{14}C$ levels for the west site might be underestimated. A sensitivity
496 analysis suggests that increasing the assumed atmospheric $\Delta\ ^{14}C$ levels from 1995 to 2005 results
497 in an improved fit of the model results for the mineral soil and humus layer $\Delta\ ^{14}C$ levels for the
498 west site. The results from the observed and simulated west site root $\Delta\ ^{14}C$ data suggest that west
499 site atmospheric $\Delta\ ^{14}C$ should be decreased and thus are inconsistent with mineral soil $\Delta\ ^{14}C$
500 data. Results from the east site show that decreasing the atmospheric $\Delta\ ^{14}C$ level results in a
501 better fit to the observed mineral soil $\Delta\ ^{14}C$ levels.

502 The model fitting process and sensitivity analysis revealed that it is possible to correctly
503 simulate the observed temporal changes in the mineral soil $\Delta\ ^{14}C$ values during the last 50 years
504 using different assumptions about the fraction of the total mineral soil carbon in the passive soil
505 organic matter pool (40-55%). We chose to fit the model using 47% since the best fit for the
506 passive fractionation for the west site was 55% and was 40% for the east site. The new estimates
507 of the turnover rates for slow and passive soil organic matter are different from the original
508 Century model estimates [*Parton et al*., 1987], with the decay rate for passive soil organic matter
509 decreased by 50% and the slow decay rate increased by 100% compared to the original values.
510 *Falloon et al*. [1998] fit the RothC model to a similar data set at the Rothamsted site in England
511 and assumed that the passive fraction (inert fraction in RothC) was only 10% of the soil organic
512 matter pool. *Petersen et al*. [2005a, 2005b] used the CN-SIM model to simulate the changes in
513 the mineral soil $\Delta\ ^{14}C$ values during the last 50 years at three sites in Europe, and found that
514 equally good fits to the observed data were between 10% and 50% of mineral soil organic matter
515 in the inert fraction. A comparison of the results from the RothC, CN-SIM, and ForCent models

shows that the peak mineral soil $\Delta\ ^{14}C$ values occurred from 1975 to 1985 and had a similar temporal pattern during the last 50 years (increasing after 1957 and then decreasing after 1985). The results from the three different models show that there is considerable uncertainly in our estimates of the fraction of total mineral soil C in passive soil organic matter and in the decay rates of the slow and passive (or inert) pools.

Observed differences between the high and low treatment mineral soil $\Delta\ ^{14}C$ values show a slight increase for the high treatments. This increase is difficult to measure because of the large amount of carbon in the 0-15 cm soil layer, and suggests that our estimate of the mixing rate of humus material into the mineral soil layer is not well bounded. We are starting a new multi-site ^{14}C surface litter layer experiment which will allow us to better quantify this flux since we will be measuring the 0-5 cm mineral soil layer instead of the 0-15 cm layer used in the Enriched Background Isotope Study experiment. Future re-sampling of the of the $\Delta\ ^{14}C$ values of the humus and mineral soil layers from the Enriched Background Isotope Study experimental plots will also provide data to better quantify the mixing rate of humus material into the mineral soil.

We used the observed Enriched Background Isotope Study $\Delta\ ^{14}C$ data for live and dead fine root and soil respiration, surface litter, and layers to validate ForCent simulations (data not used for model calibration) of the movement of ^{14}C into the soil pools. ForCent correctly simulated the observed higher $\Delta\ ^{14}C$ values for live and dead roots in the west site and also the general pattern of decreasing $\Delta\ ^{14}C$ values following the 1999 exposure to elevated ^{14}C atmospheric levels. However, the model did tend to overestimate the $\Delta\ ^{14}C$ values for live roots in the west site. The sensitivity analysis showed that increasing the atmospheric $\Delta\ ^{14}C$ values in the west site improved the fit of the model to the humus and mineral soil $\Delta\ ^{14}C$ values. This increase caused

the model to exaggerate the existing overestimate of the live and dead root $\Delta\ ^{14}C$ values for the west site.

A comparison of the observed vs. simulated soil respiration $\Delta\ ^{14}C$ values shows that the model correctly simulated the major Enriched Background Isotope Study treatment differences and the movement of $\Delta\ ^{14}C$ labeled leaf and root carbon into soil organic matter pools (observed vs. simulated $r^2 = 0.75$ overall). The model tended to underestimate the observed increase in mineral soil respiration $\Delta\ ^{14}C$ values for the high labeled litter treatments. This could result from an underestimate of the amount of labile surface litter material leaching out of the surface litter layer into the mineral soil layer and then quickly lost due to microbial respiration. Dissolved organic carbon flux measurements for the Enriched Background Isotope Study experiment [*Fröberg et al*., 2007; *Fröberg et al*., 2009] show that a substantial amount of dissolved organic carbon is leached out of the surface litter layer (surface litter, humus layers) into the mineral soil layer and quickly lost as soil respiration. These data from *Fröberg et al*. [2009] are currently being used to develop a new dissolved organic carbon leaching submodel in ForCent.

Acknowledgements

Funding for the Enriched Background Isotope Study project was provided by the U.S. Department of Energy, Office of Science, Office of Biological and Environmental Research under Contract No. DE-AC02-05CH11231, as a part of the Terrestrial Carbon Processes (TCP) Program.

561 **References**

562 Aerts, R., H. de Caluwe, and B. Beltman, (2003), Plant community mediated vs. nutritional
563 controls on litter decomposition rates in grasslands, *Ecology*, 84(12), 3198-3208.
564 Cisneros-Dozal, L. M., S. E. Trumbore, and P. J. Hanson, (2007), Effect of moisture on leaf litter
565 decomposition and its contribution to soil respiration in a temperate forest, J. *Geophys.*
566 *Res*., 112, G01013, doi:10.1029/2006JG000197.
567 Coleman, K., and D. S. Jenkinson (1996), RothC-26.3 — A model for the turnover of carbon in
568 soil, in *Evaluation of soil organic matter models using existing long-term datasets*, vol.
569 38, edited by S. Powlson, P. Smith, and J. U. Smith, pp. 237-246, Springer, Berlin
570 DelGrosso, S. J., A. R. Mosier, and W. J. Parton (2005), DAYCENT model analysis of past and
571 contemporary soil N_2O and net greenhouse gas flux for major crops in the USA, *Soil and*
572 *Tillage Research*, 83, 9-24.
573 DelGrosso, S. J., W. J. Parton, and A. R. Mosier (2001a), Simulated interaction of carbon
574 dynamics and nitrogen trace gas fluxes using the DAYCENT model, in *Modeling Carbon*
575 *and Nitrogen Dynamics for Soil Management*, edited by M. Schaffer, L. Ma, and S.
576 Hansen, CRC Press, Boca Raton, Florida.
577 DelGrosso, S. J., W. J. Parton, and A. R. Mosier (2001b), Simulated effects of land use, soil
578 texture, and precipitation on N gas emissions using DAYCENT, in *Nitrogen in the*
579 *Environment: Sources, Problems, and Management*, edited by R. F. Follett, and J. L.
580 Hatfield, Elsevier Science Publishers, The Netherlands.
581 DeLucia, E. H., J. E. Drake, R. B. Thomas, M. Gonzalez-Meier (2007), Forest carbon use
582 efficiency: is respiration a constant fraction of gross primary production? *Global Change*
583 *Biology*, 13, 1157-1167.

584 Dornbush, M. E., T. M. Isenhart, J. W. Raich (2002), Quantifying fine-root decomposition: An
585 alternative to buried litterbags, *Ecology*, 83, 2985-2990.
586 Eitzinger, J., W. J. Parton, and M. Hartman (2000), Improvement and validation of a daily soil
587 temperature submodel for freezing/thawing periods, *Soil Sci.*, 165(7), 525-534.
588 Follett, R. F., E. A. Paul, and E. G. Pruessner (2007), Soil carbon dynamics during a long-term
589 incubation study involving ^{13}C and ^{14}C measurements, *Soil Biol. Biochem*., 172, 189-208.
590 Falloon, P. D., P. Smith, and K. Coleman (1998), Estimating the size of the inert organic matter
591 pool for use in the Rothamsted carbon model, *Soil Biol. Biochem*., 28, 1367-1372.
592 Fröberg, M., P. J. Hanson, S. E. Trumbore, C. W. Swanston, and D. E. Todd (2009), Flux of
593 carbon from ^{14}C-enriched leaf litter throughout a forest soil mesocosm, *Geoderma*, 149,
594 181-188.
595 Fröberg, M., P. M. Jardine, and P. J. Hanson (2007), Low dissolved organic carbon input from
596 fresh litter to deep mineral soils. *Soil Sci. Soc. Am. J*., 71, 347-354.
597 Frolking, S. E., A. R. Mosier, and D. S. Ojima (1998), Comparison of N_2O emissions from soils
598 at three temperate agricultural sites: simulations of year-round measurements by four
599 models, *Nutrient Cycling in Agroecosystems*, 52, 77-105.
600 Hanson, P. J., C. W. Swanston, and C. T. Gartgen Jr. (2005), Reconciling change in Oi-horizon
601 carbon-14 with mass loss for an oak forest, *Soil Sci. Soc. Am. J*., 69, 1492-1502.
602 Hanson, P. J., D. E. Todd, and D. C. West (2003a), Tree and sapling growth and mortality, in
603 *North American Temperate Deciduous Forest Responses to Changing Precipitation*
604 *Regimes*, edited by P. J. Hanson, and S. D. Wullschleger, Springer, New York.
605 Hanson, P. J., E. G. O'Neill, and M. L. S. Chambers (2003b), Soil respiration and litter
606 decomposition, in *North American Temperate Deciduous Forest Responses to Changing*

Precipitation Regimes, edited by P. J. Hanson, and S. D. Wullschleger, Springer, New York.

Hobbie, S. E. (1996), Temperature and plant species control over litter decomposition in Alaskan tundra. *Ecological Monographs*, 66, 503-522.

Jenkinson, D. S. (1971) Studies on the decomposition of ^{14}C-labeled organic matter in soil, *Soil Sci.*, 111, 64-70.

Joslin, J. D., J. B. Gaudinski, and M. S. Torn (2006), Fine root turnover patterns and their relationship to root diameter and soil depth in a ^{14}C-labeled hardwood forest, *New Phytologist*, 172, 523-535.

Kelly, R. H., W. J. Parton, and M. D. Hartman (2000), Intra- and inter-annual variability of ecosystem processes in shortgrass steppe, *J. Geophys. Res.: Atmospheres*, 105, 20,093-20,100.

Kelly, R. H., W. J. Parton, and C. J. Crocker (1997), Simulating trends in soil organic carbon in long-term experiments using the Century model, *Geoderma*, 81, 75-90.

Li, C., S. Frolking, and R. Harriss, (1994), Modeling Carbon Biogeochemistry in Agricultural Soils, *Global Biogeochem. Cycles* 8(3), 237-254.

Litton, C. M., M. G. Ryan, J. W. Raich (2007), Carbon allocation in forest ecosystems, *Global Change Biology*, 13, 2089-2109.

Lousier, J. D., and D. Parkinson (1976), Litter decomposition in a cool temperature deciduous forest, *Can. J. Botany*, 54, 419-436.

Luo, Y., D. Gerten, G. Le Marie, W. J. Parton, E. Weng, X. Zhou, C. Keough, C. Beier, P. Ciais, W. Cramer, J. S. Dukes, B. Emmett, P. J. Hanson, A. Knapp, S. Linder, D. Nepstad, and L. Rustad (2008), Modeled interactive effects of precipitation, temperature, and CO_2 on

ecosystem carbon and water dynamics in different climatic zones, *Global Change Biology*, 14, 1986-1999.

McClaran, M. P., and G. R. McPherson (1995), Can soil organic carbon isotopes be used to describe grass-tree dynamics at a savanna-grassland ecotone and within the savanna? *J. Vegetation Science*, 6(6), 857-862.

McClaugherty, C. A., J. Pastor, and J. D. Aber (1985), Forest litter decomposition in relation to soil nitrogen dynamics and litter quality, *Ecology*, 66(1), 266-275.

Meentemeyer, V. (1978), Macroclimate the lignin control of litter decomposition rates, *Ecology*, 59(3), 465-472.

Melillo, J. M., J. D. Aber, and J. F. Muratore (1982), Nitrogen and lignin control of hardwood leaf litter decomposition dynamics, *Ecology*, 63(3), 621-626.

Osher, L. J., P. A. Matson, and R. Amundson (2003), Effect of land use change on soil carbon in Hawaii, *Biogeochemistry*, 65(2), 213-232.

Parton, W. J., W. L. Silver, and I. C. Burke (2007a), Global-scale similarities in nitrogen release patterns during long-term decomposition, *Science*, 315, 361-164.

Parton, W. J., J. A. Morgan, G. Wang (2007b), Projected ecosystem impact of the prairie heating and CO_2 enrichment experiment, *New Phytologist*, 174, 823-834.

Parton, W. J., E. A. Holland, and S. J. Del Grosso (2001), Generalized model for NO_x and N_2O emissions from soils, *J. Geophys. Res*., 106, 17403-17420.

Parton, W. J., M. Hartman, and D. S. Ojima (1998), DAYCENT and its land surface submodel: description and testing, *Global and Planetary Change*, 19, 35-48.

Parton, W. J., D. S. Schimel, and C. V. Cole (1987), Analysis of factors controlling SOM levels in Great Plains grasslands, *Soil Sci. Soc. Am. J*., 51, 1173-1179.

653 Parton, W. J., J. S. Singh, and D. C. Coleman (1978) A model of production and turnover of
654 roots in shortgrass prairie, *J. Appl. Ecology*, 47, 515-542.
655 Paul, E. A., R. F. Follett, and S. W. Leavitt (1997), Radiocarbon dating for determination of
656 SOM pool sizes and dynamics, *Soil Sci. Soc. Am. J.*, 61, 1058-1067.
657 Pepper, D. A., S. J. DelGrosso, and R. E. McMurtrie (2005) Simulated carbon sink response of
658 shortgrass steppe, tallgrass prairie, and forest ecosystems to rising (CO_2) temperature and
659 nitrogen input, *Global Biogeochem. Cycles*, 19, GB1004, doi:10.1029/2004GB002226.
660 Petersen, B. M., J. Berntsen, and S. Hansen (2005a), CN-SIM - a model for the turnover of
661 SOM. I: Long term carbon development, *Soil Biol. Biochem*., 37, 359-374.
662 Petersen, B. M., L. S. Jensen, J. Berntsen, and S. Hansen (2005b), CN-SIM - a model for the
663 turnover of SOM. II: Short term carbon and nitrogen development, *Soil Biol. Biochem*.,
664 37, 375-393.
665 Riley, W. J., J. B. Gaudinski, M. S Torn, J. D. Joslin, and P. J. Hanson (2009), Fine-root
666 mortality rates in a temperate forest: estimates using radiocarbon data and numerical
667 modeling, *New Phytologist,* 184, 387-398.
668 Running, S. W., and J. C. Coughlan (1988), A general model of forest ecosystem processes for
669 regional applications, I. Hydrologic balance, canopy gas exchange and primary
670 production processes, *Ecological Modelling*, 42, 125-154.
671 Ryan, M. G., R. M. Hubbard, S. Pongracic, R. J. Raison, R. E. McMurtrie (1996), Foliage, fine-
672 root, woody-tissue and stand respiration in *Pinus radiata* in relation to nitrogen status,
673 *Tree Physiology*, 16, 333-343.
674 Ryan, M. G., S. T. Gower, and R. M. Hubbard (1995), Woody tissue maintenance respiration of
675 four conifers in contrasting climates, *Oecologia*, 101, 133-140.

676 Shanks, R. E., and J. S. Olson (1961) First-year breakdown of leaf litter in southern Appalachian
677 forests, *Science*, 134, 194-195.
678 Steuter, A. A., B. Jasch, and J. Ihnen (1990) Woodland/grassland boundary changes in the
679 middle Niobrara Valley of Nebraska identified by δ^{13}c values of SOM, *American*
680 *Midland Naturalist*, 124(2), 301-308.
681 Swanston, C. W., M. S. Torn, and P. J. Hanson (2005), Initial characterization of processes of
682 soil carbon stabilization using forest stand-level radiocarbon enrichment, *Geoderma*, 128,
683 52-62.
684 Trofymow, J. A., T. R. Moore, and B. D. Titus (2002), Rates of litter decomposition over 6 years
685 in Canadian forests: influence of litter quality and climate, *Can. J. Forest Research*, 32,
686 789-804.
687 Trumbore, S., J. B. Gaudinski, and P. J. Hanson (2002), A whole-ecosystem carbon-14 label in a
688 temperate forest, *EOS*, 83(265), 267-268.
689 Wang, Y, R. Amundson, and S. Trumbore (1996), Radiocarbon dating of SOM, *Quaternary*
690 *Research*, 45(3), 282-288.
691 Waring, R. H., J. J. Landsberg, M. Williams (1998), Net primary production of forests: a
692 constant fraction of gross primary production? *Tree Physiology*, 18, 129-134.
693 Wieder, R. K., G. E. Lang (1982), A critique of the analytical methods used in examining
694 decomposition data obtained from litter bags, *Ecology*, 63(6), 1636-1642.

Table 1. Comparison of observed and simulated plant production for leaves, fine roots, total wood production, total production, and soil respiration from 1993-2000 at the Oak Ridge site [*Hanson et al*., 2003a, 2003b]. The table also contains the maximum and minimum annual flux values during the time period, the mean absolute error and r^2 values for the model vs. observed data comparison.

Annual Plant Production	**Simulated mean (g C/m^2 y^{-1})**	**Observed mean (g C/m^{-2} y^{-1})**	**Mean absolute error* (g C m^{-2} y^{-1})**	**Model vs. observed data (r^2)**
Leaf	246.0 (230 – 249)	240.0 (233 – 258)	14.0	0.61
Wood (branch + Large wood + Coarse roots)	267.0 (99 – 374)	264.0 (200 – 348)	43.0	0.60
Fine roots	116.0 (67 – 136)	113.0 (89 – 153)	17.0	0.38
Total production	629.0 (413 – 753)	616.0 (529 – 747)	55.0	0.53
Soil respiration	916.0 (809 – 1024)	941.0 (808 – 976)	52.0	0.77**

* Mean absolute error $\frac{\sum_{t=1}^{N} \text{abs}\,(S_i - O_i)}{N}$ where Oi is the observed value, Si is the simulated value and N is the number of observations.

** Data from 1998 and 1999 were excluded because of uncertainty about which model was correct (see discussion in text)

Table 2: Comparison of the observed and simulated mean $\Delta\ ^{14}C$ for surface litter, humus, and mineral soil for the east and west sites and high and low treatments. The mean absolute error for the surface litter, humus, and mineral soil layer is also presented.

		Observed Mean $\Delta\ ^{14}C$ (‰)	**Simulated Mean $\Delta\ ^{14}C$ (‰)**	**Mean Absolute Error***
Surface Litter				
East	High	503.0	478.0	52.0
	Low	211.0	211.0	27.0
West	High	646.0	628.0	42.0
	Low	358.0	361.0	48.0
Humus				
East	High	266.0	200.0	21.0
	Low	200.0	201.0	8.0
West	High	405.0	351.0	53.0
	Low	357.0	272.0	85.0
Carbon				
Soil East	High	119.0	125.0	12.0
	Low	108.0	122.0	14.0
Soil West	High	146.0	142.0	10.0
	Low	143.0	139.0	8.0

*Mean absolute error $= \frac{\sum_{i=1}^{N} \text{abs}\ (O_i - S_i)}{\text{N}}$ where Oi is the observed value, Si is the simulated value, and N is the number of observations.

Figure Captions

Figure 1. Flow diagram and components of the ForCent forest growth model. The ForCent model simulates $\Delta^{14}C$ and $\Delta^{13}C$ content for all of the carbon state variables and flows in the model (e.g., soil respiration).

Figure 2. Revised flow diagram for the surface organic and mineral soil layers in the ForCent model.

Figure 3. Fine root growth submodel used in the ForCent model. This model is based on the model developed by *Parton et al*. [1978].

Figure 4. (a) Impact of soil relative water content [F (W)] on decomposition of ForCent soil pools; (b) the effect of soil temperature [F (T)]) on the decomposition of soil pools; and (c) observed atmospheric $\Delta^{14}C$ levels from 1950 to 2005 for the east and west EBIS experimental sites. Atmospheric $\Delta^{14}C$ values for the east and west sites from 1995 to 2006 are based on observed average wood cellulose values for these sites.

Figure 5. Simulated vs. observed $\Delta^{14}C$ content of the surface litter layer for the (a) east, and (b) west sites. Simulated vs. observed $\Delta^{14}C$ content of the humus layer for the (c) east, and (d) west EBIS sites. Data is presented for both the low and high litter treatments in addition to the standard deviation of the observed data.

Figure 6. Simulated vs. observed mineral soil layer $\Delta^{14}C$ content for the (a) low east site from 1950 to 2005; (b) low and high east site mineral soil $\Delta^{14}C$ values from 1995 to 2005; and (c) west site (high and low treatments) mineral soil $\Delta^{14}C$ values from 1995 to 2005. Data from the Δ

21 ^{14}C levels prior to 2001 came from the Walker branch site, and standard deviation of the
22 observed data is plotted.

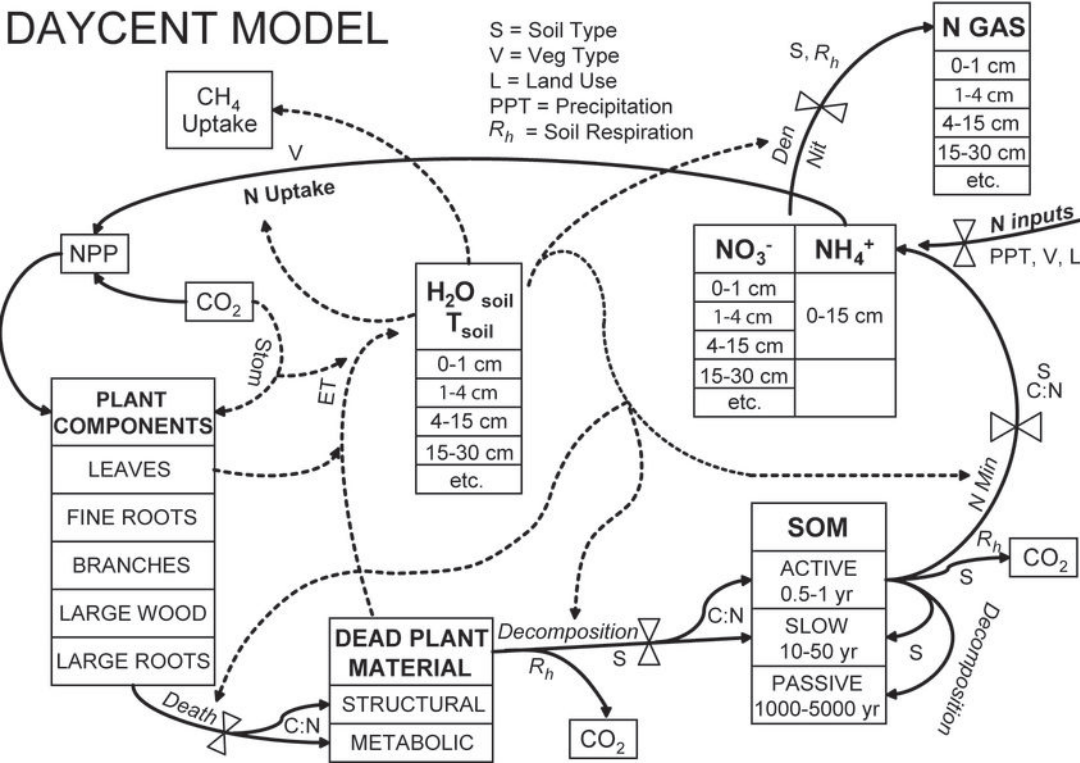
23 Figure 7. Simulated vs. observed $\Delta\ ^{14}C$ levels for the (a) dead roots in the east and west sites; (b)
24 live roots in the east and west sites; and (c) a comparison of simulated $\Delta\ ^{14}C$ values for live
25 juvenile roots with the observed root screen new root growth $\Delta\ ^{14}C$ data for the east and west
26 sites (plus the standard deviation of the observed data).

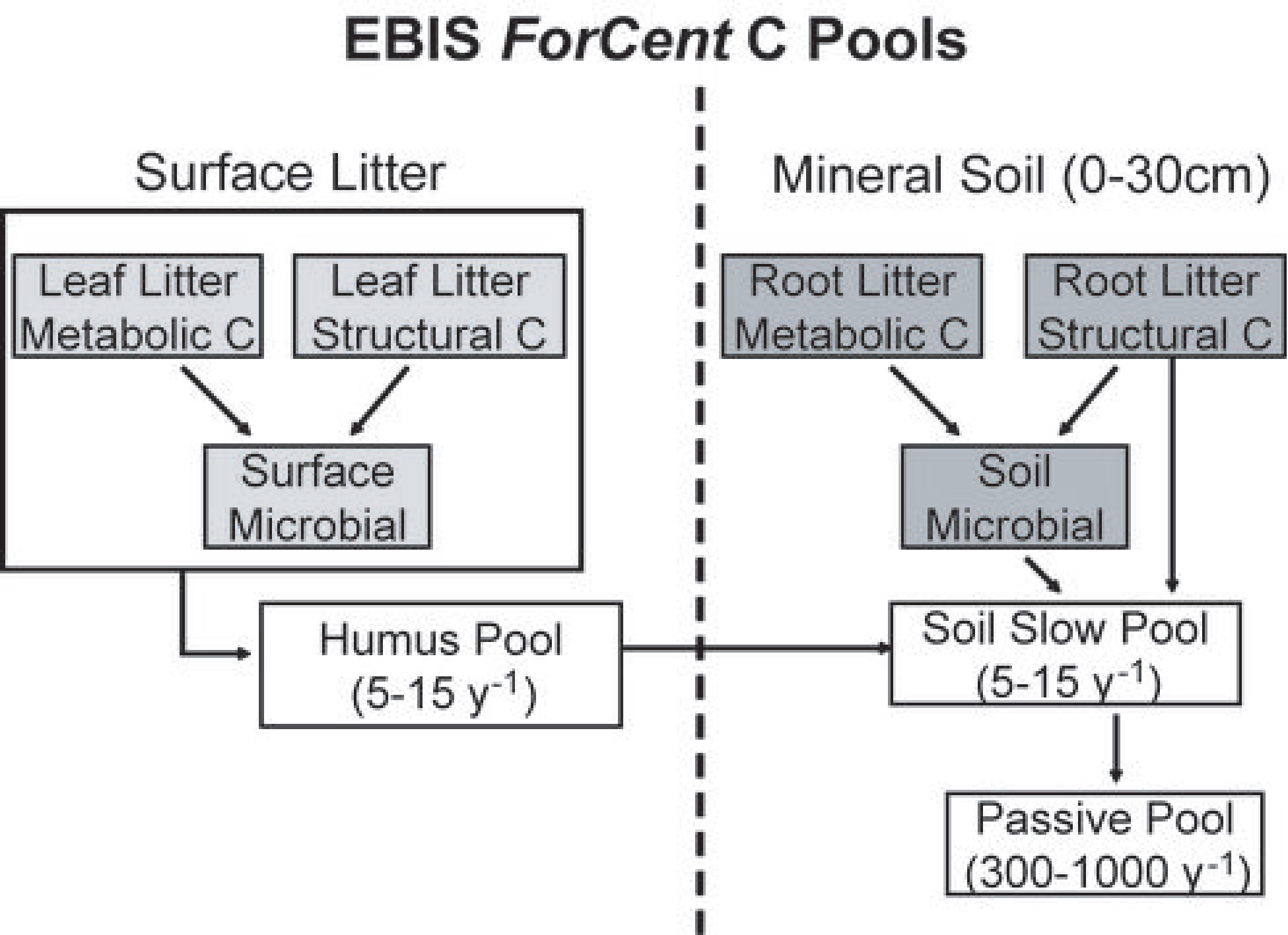
27 Figure 8. (a) Simulated total soil respiration from August 2003 in response to rainfall events; and
28 (b) observed vs. simulated $\Delta\ ^{14}C$ of total soil respiration for the high and low treatments at the
29 east site [*Cisneros-Dozal et al*., 2007].

30 Figure 9. Comparison of observed and simulated average $\Delta\ ^{14}C$ values for total soil respiration,
31 litter respiration (surface litter plus humus layers), and mineral soil respiration from 2002 to
32 2004 for (a) east and west site high and low treatments; and (b) average humus and surface litter
33 $\Delta\ ^{14}C$ respiration from the east and west site high and low treatments for 2001.

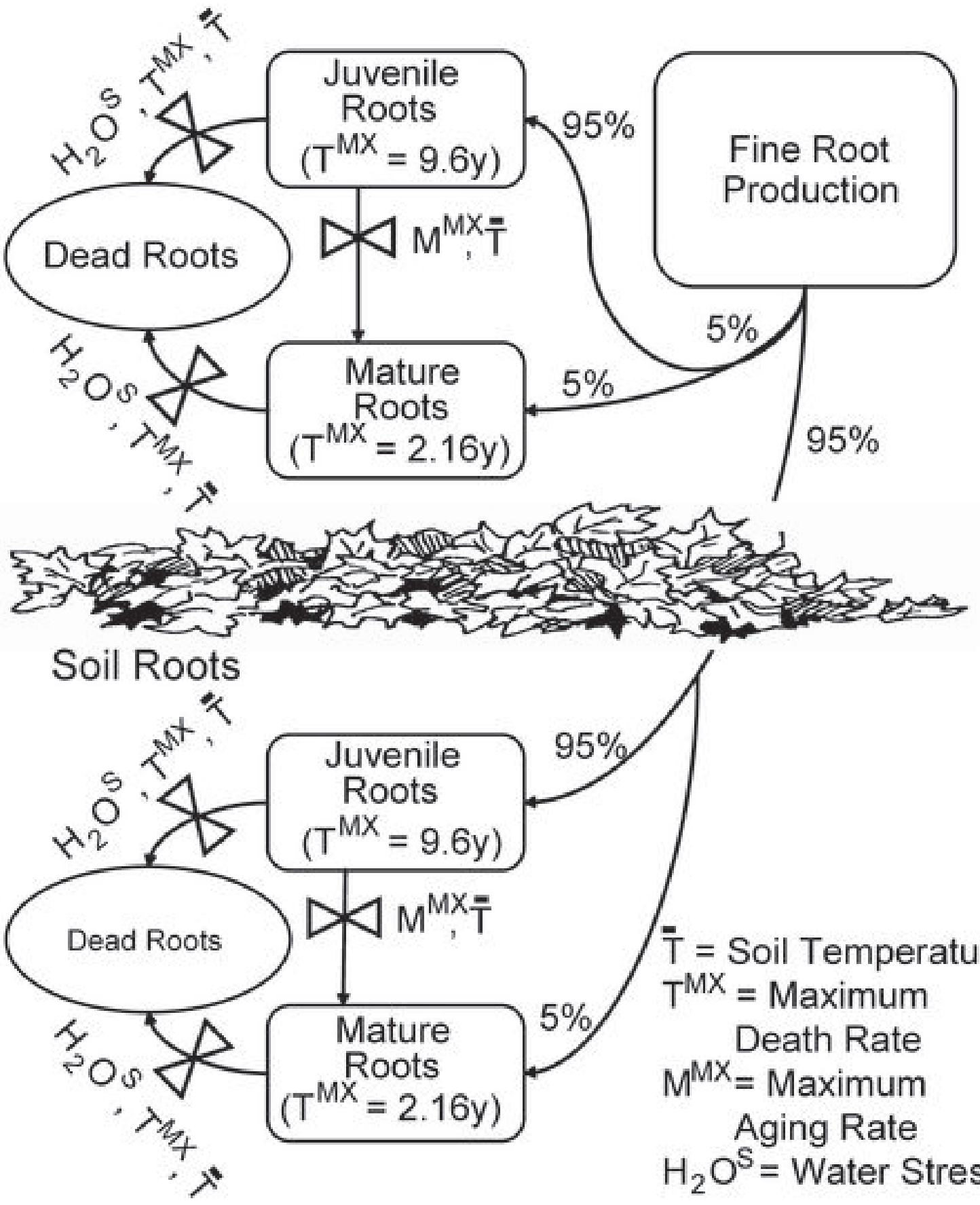
34 Figure 10. Comparison of observed and simulated mineral soil $\Delta\ ^{14}C$ values for the control runs,
35 and ± 30% atmospheric $\Delta\ ^{14}C$ runs for (a) the east high treatment; (b) east low treatment; (c) west
36 high treatment; and (d) west low treatment. Control atmospheric $\Delta\ ^{14}C$ values for the east and
37 west sites from 1995 to 2006 were assumed to be equal to the average new cellulose wood
38 growth $\Delta\ ^{14}C$ values in the east and west sites.

39 Figure 11. Comparison of the observed and simulated mineral soil $\Delta\ ^{14}C$ values for the 47%
40 passive SOM pool run, 40% passive SOM pool run, and 57% passive SOM pool run for the (a)
41 east high treatment; (b) east low treatment; (c) west high treatment; and (d) west low treatment.

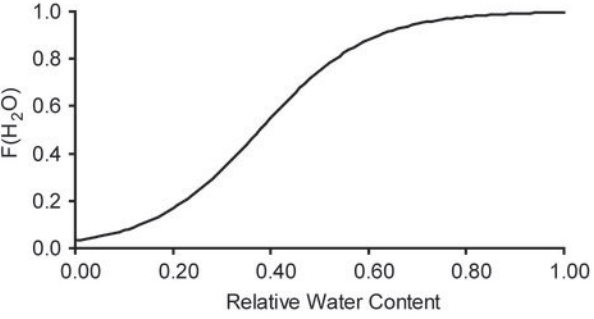

DAYCENT MODEL
S = Soil Type
V = Veg Type
L = Land Use
PPT = Precipitation
R_h = Soil Respiration
CH_4 Uptake
V
N Uptake
NPP
CO_2
Storm
ET
H_2O soil
T_{soil}
0-1 cm
1-4 cm
4-15 cm
15-30 cm
etc.
PLANT COMPONENTS
LEAVES
FINE ROOTS
BRANCHES
LARGE WOOD
LARGE ROOTS
Death
C:N
DEAD PLANT MATERIAL
STRUCTURAL
METABOLIC
R_h
CO_2
Decomposition
S
C:N
SOM
ACTIVE 0.5-1 yr
SLOW 10-50 yr
PASSIVE 1000-5000 yr
R_h
CO_2
S
Decomposition
N Min
S
C:N
NO_3^-
NH_4^+
0-15 cm
N inputs
PPT, V, L
S, R_h
Den
Nit
N GAS
0-1 cm
1-4 cm
4-15 cm
15-30 cm
etc.


EBIS ForCent C Pools
Surface Litter
Mineral Soil (0-30cm)
Leaf Litter Metabolic C
Leaf Litter Structural C
Root Litter Metabolic C
Root Litter Structural C
Surface Microbial
Soil Microbial
Humus Pool (5-15 y-1)
Soil Slow Pool (5-15 y-1)
Passive Pool (300-1000 y-1)

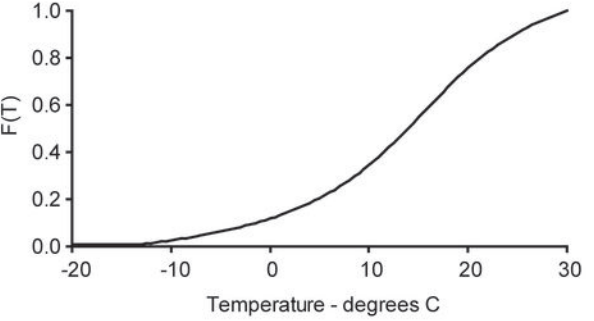
Fine Root Model



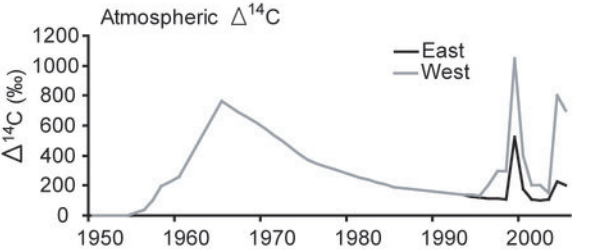
a.

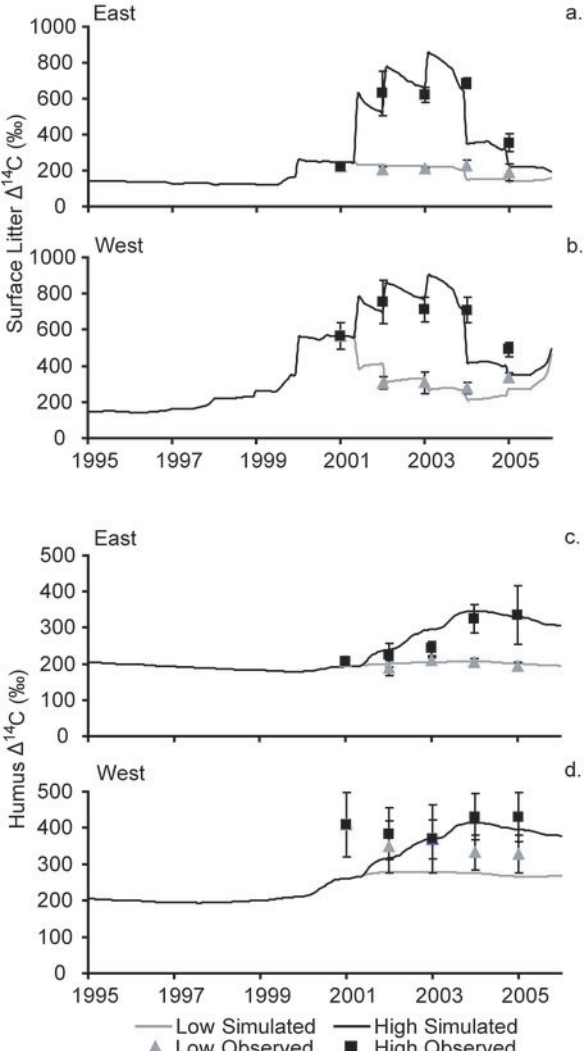

1.0
0.8
0.6
0.4
0.2
0.0
F(H2O)
0.00
0.20
0.40
0.60
0.80
1.00
Relative Water Content

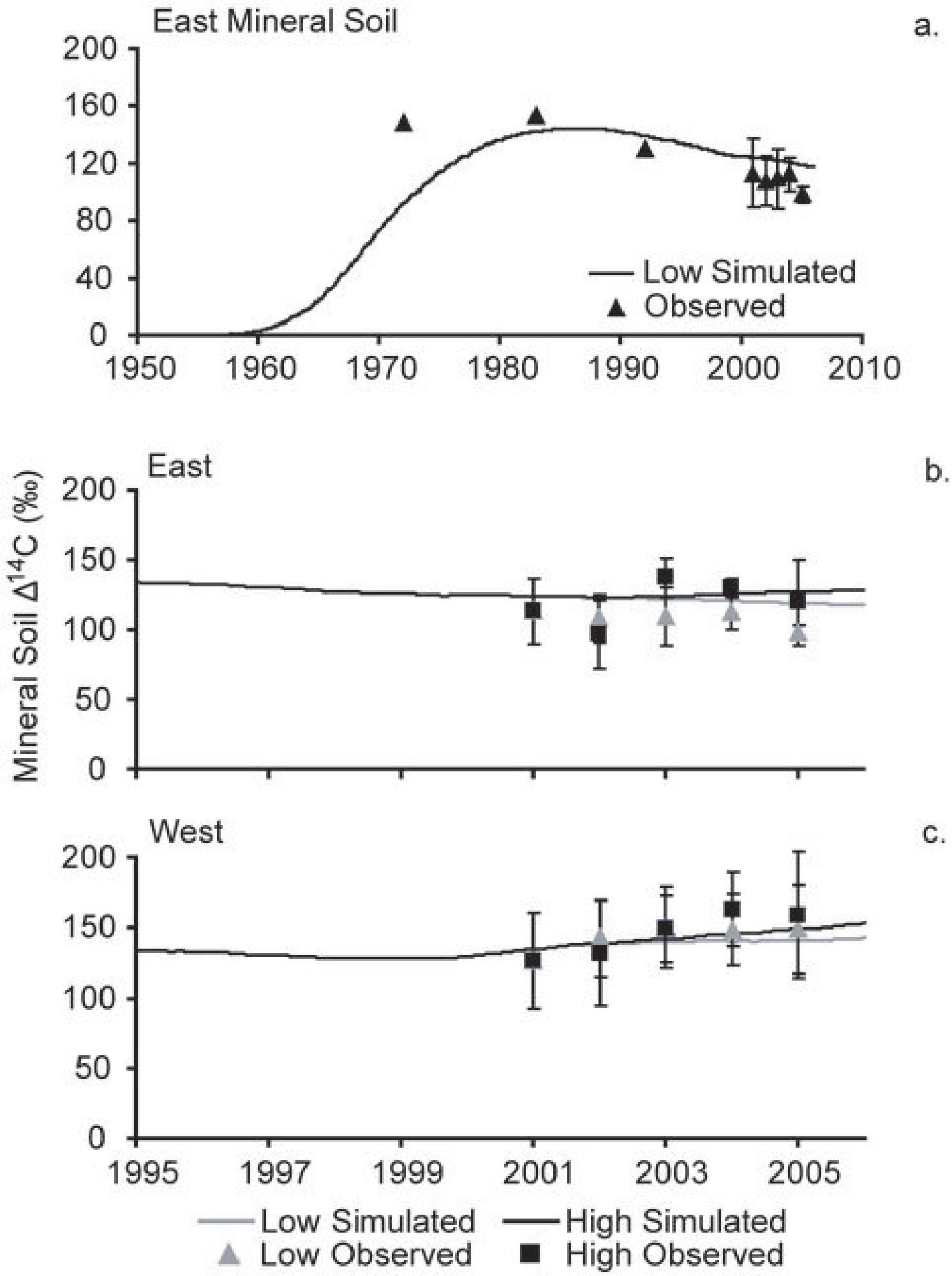
b.

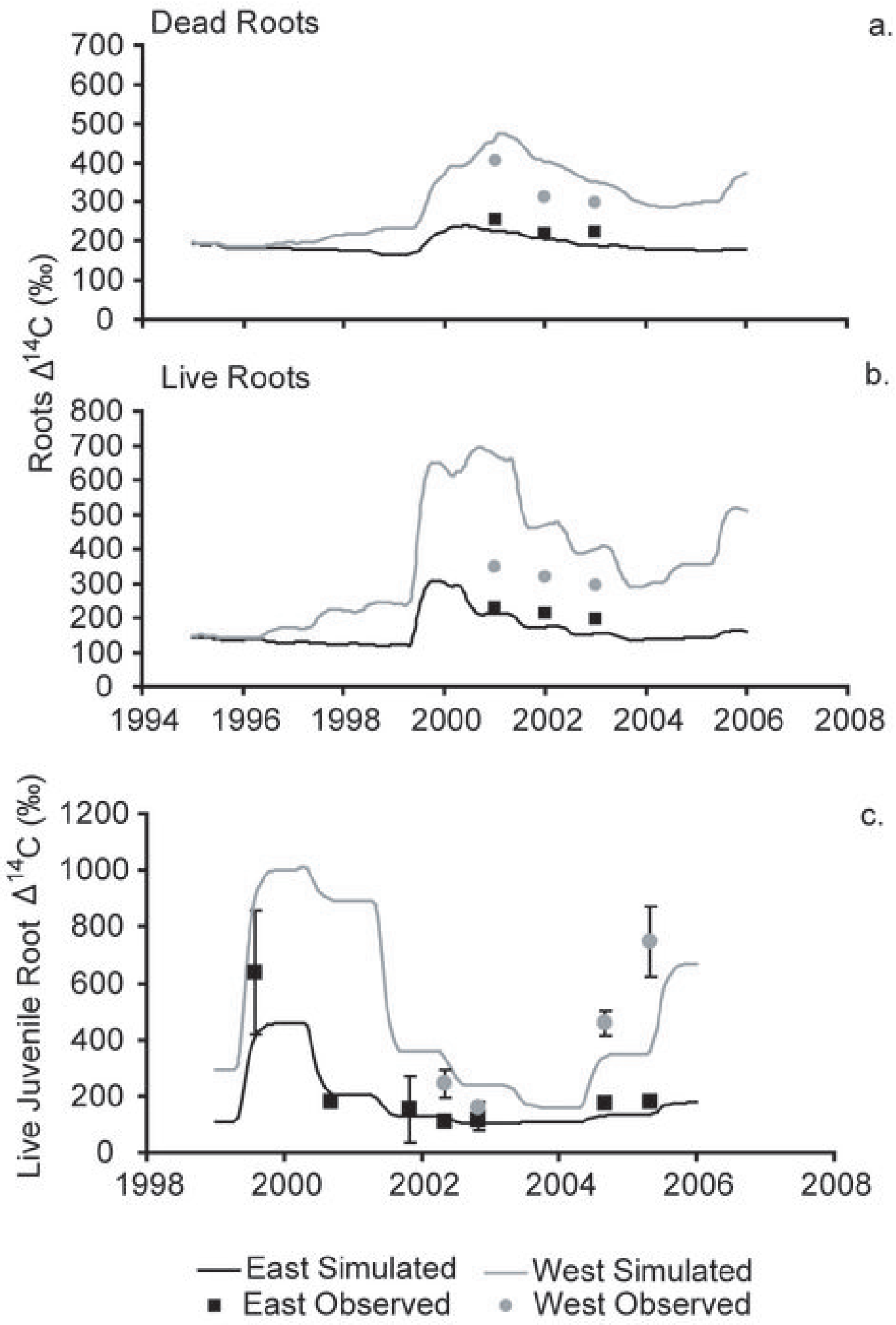

1.0
0.8
0.6
0.4
0.2
0.0
F(T)
-20
-10
0
10
20
30
Temperature - degrees C

c.

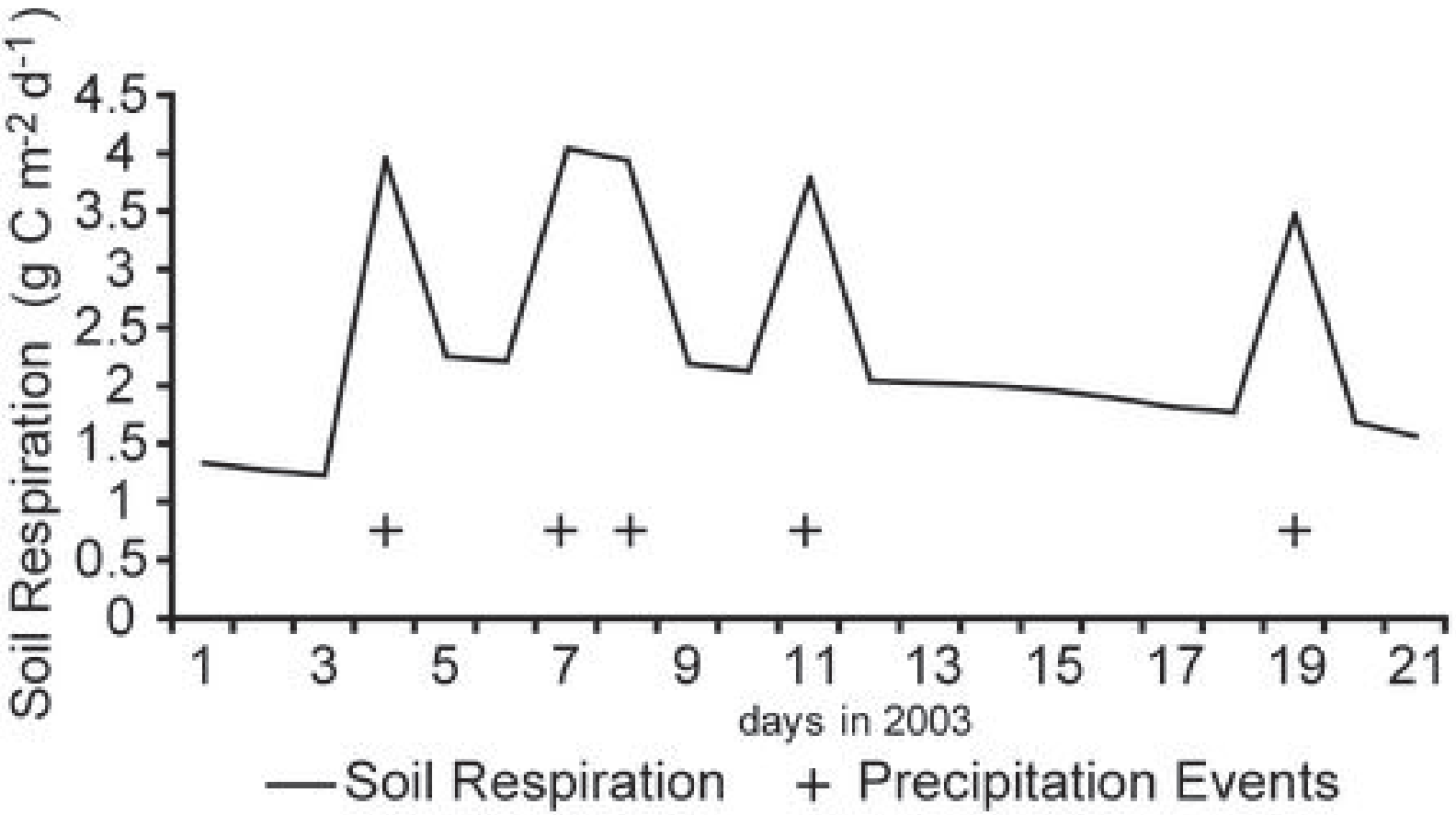

Atmospheric Δ14C
East
West
1200
1000
800
600
400
200
0
Δ14C (‰)
1950
1960
1970
1980
1990
2000


East
a.
1000
800
600
400
200
0
Surface Litter Δ14C (‰)
West
b.
1000
800
600
400
200
0
1995
1997
1999
2001
2003
2005
East
c.
500
400
300
200
100
0
Humus Δ14C (‰)
West
d.
500
400
300
200
100
0
1995
1997
1999
2001
2003
2005
Low Simulated
High Simulated
Low Observed
High Observed

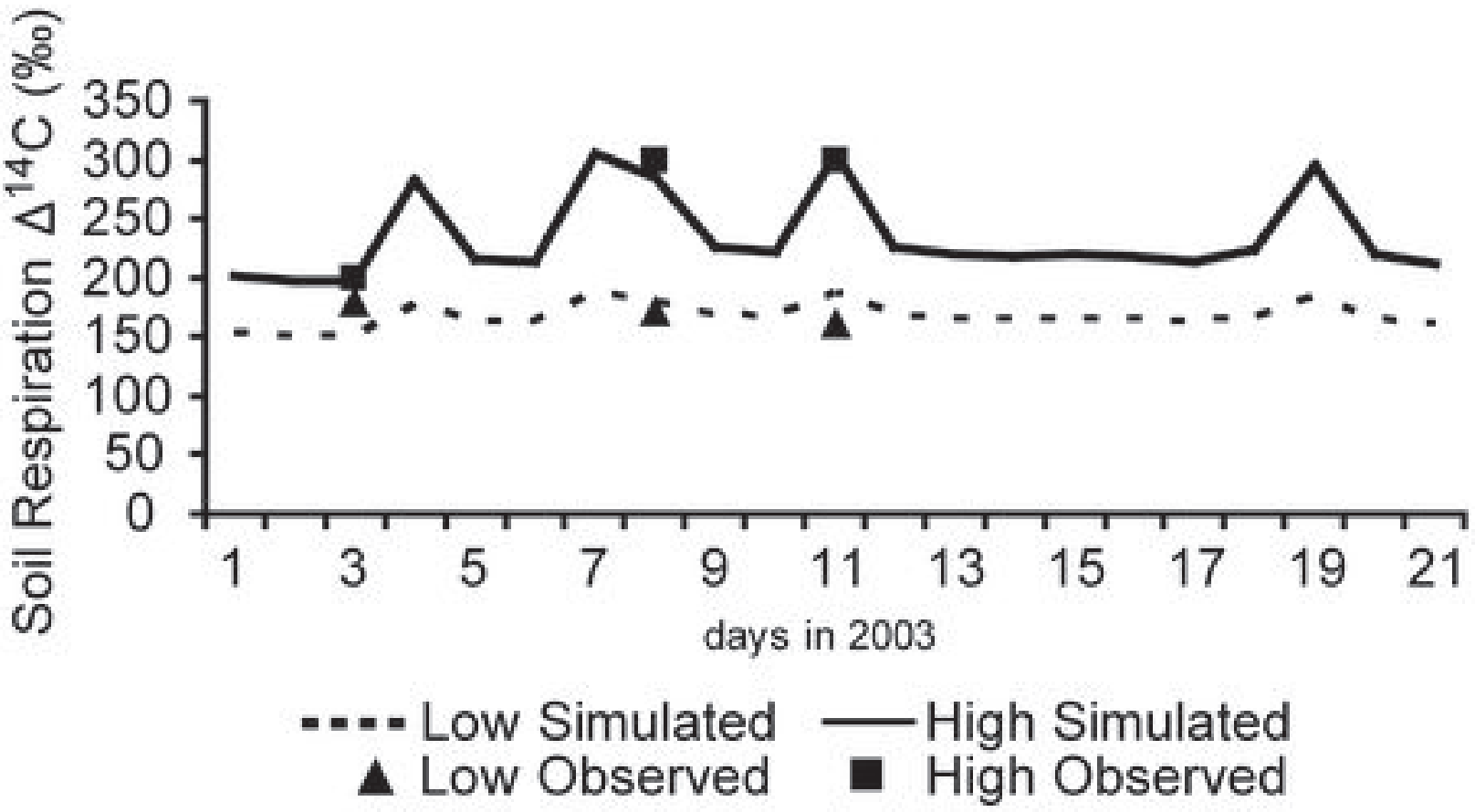

East Mineral Soil
a.
200
160
120
80
40
0
1950
1960
1970
1980
1990
2000
2010
Low Simulated
Observed
East
b.
Mineral Soil Δ14C (‰)
200
150
100
50
0
West
c.
200
150
100
50
0
1995
1997
1999
2001
2003
2005
Low Simulated
High Simulated
Low Observed
High Observed

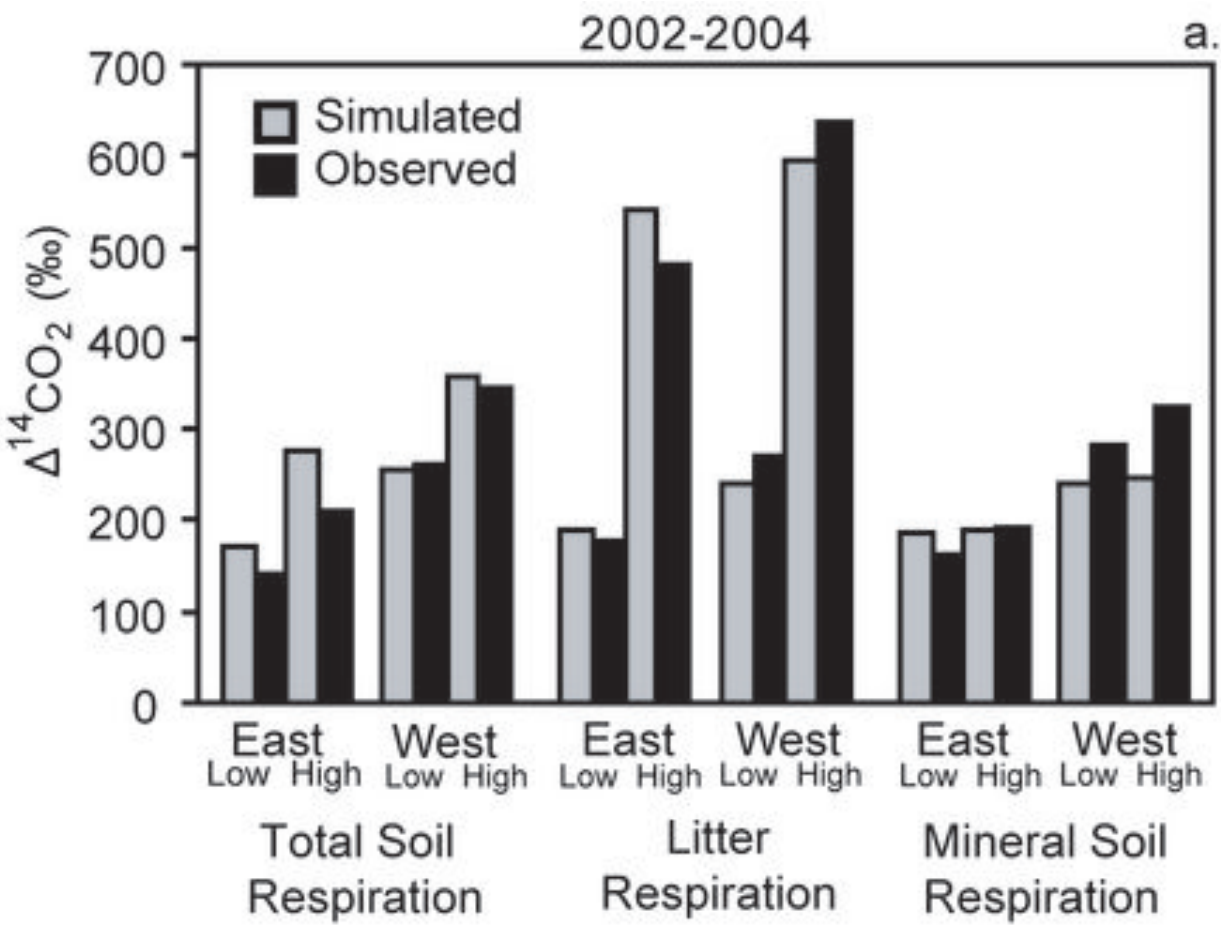

Dead Roots
a.
700
600
500
400
300
200
100
0
Roots Δ14C (‰)
Live Roots
b.
800
700
600
500
400
300
200
100
0
1994
1996
1998
2000
2002
2004
2006
2008
Live Juvenile Root Δ14C (‰)
c.
1200
1000
800
600
400
200
0
1998
2000
2002
2004
2006
2008
East Simulated
West Simulated
East Observed
West Observed

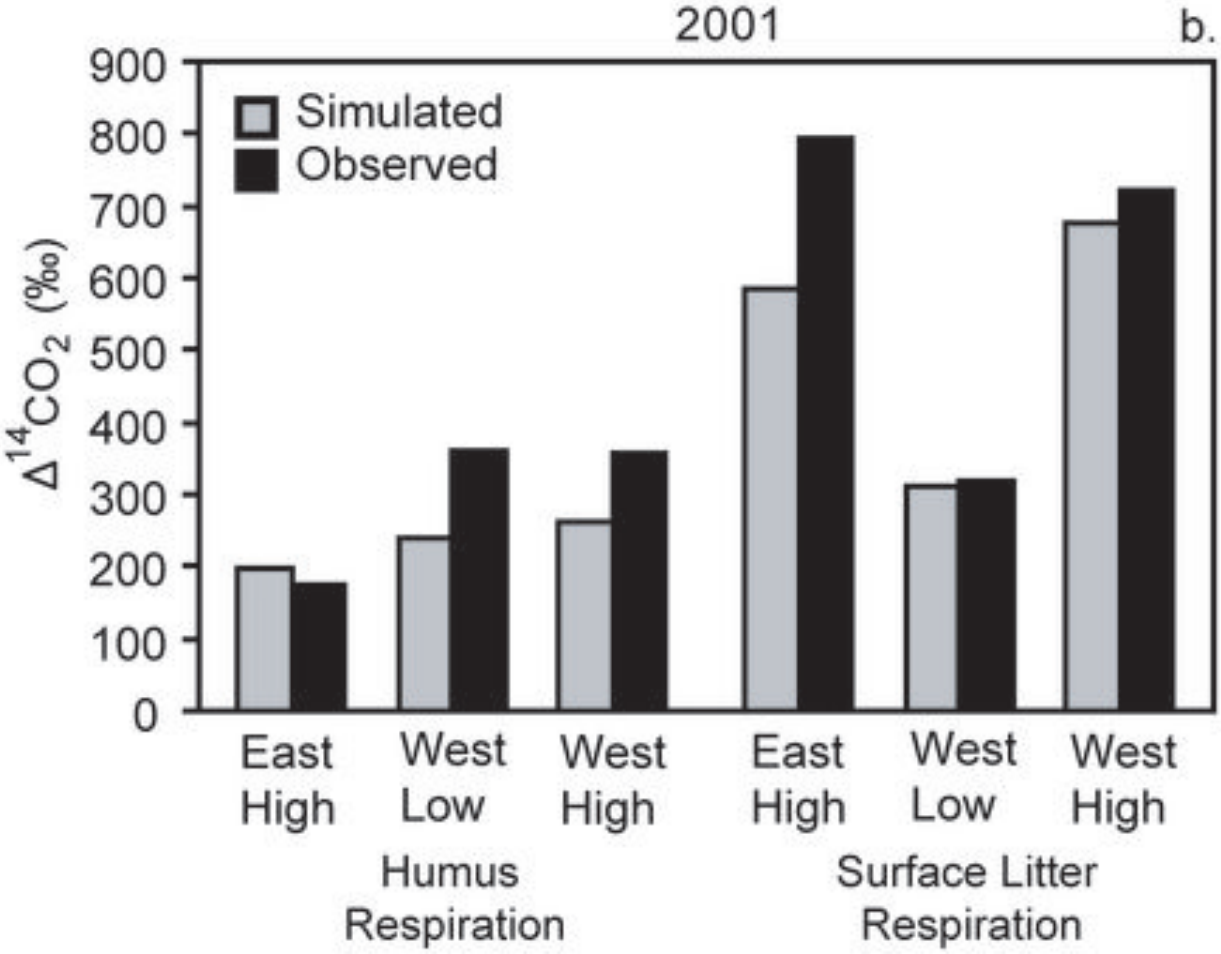
a.

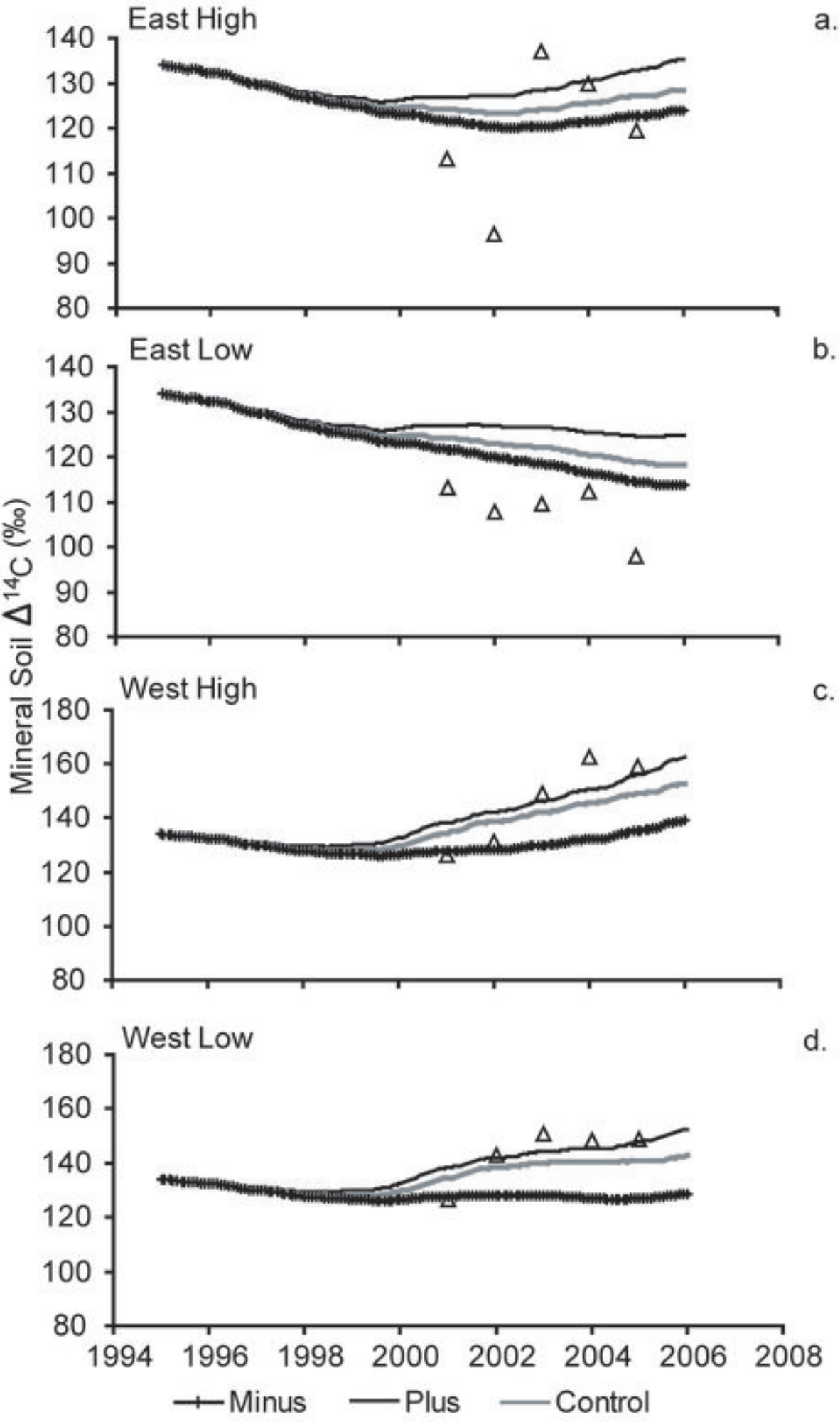

Soil Respiration (g C m-2 d-1)
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
1
3
5
7
9
11
13
15
17
19
21
days in 2003
Soil Respiration
+ Precipitation Events

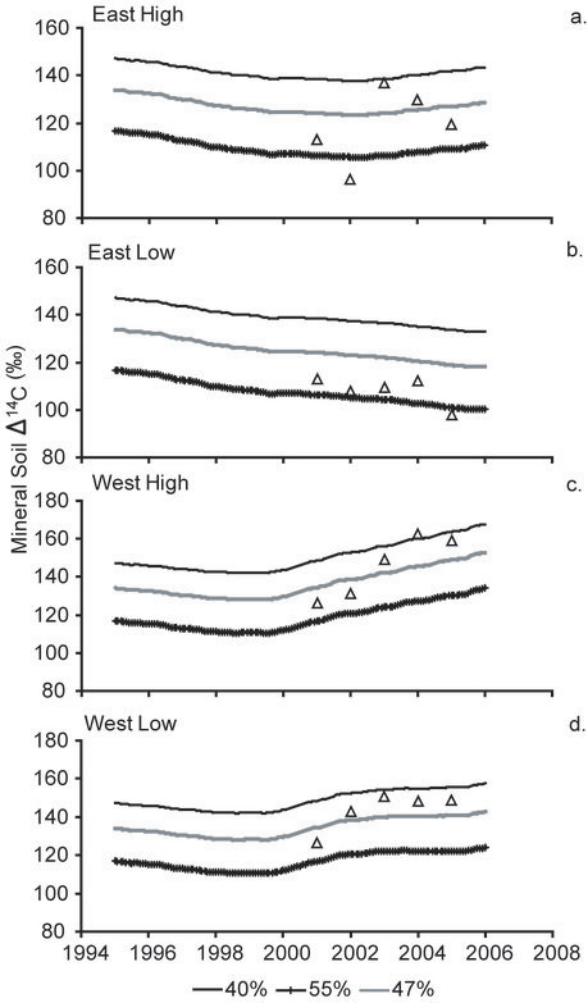
b.


Soil Respiration Δ14C (‰)
350
300
250
200
150
100
50
0
1
3
5
7
9
11
13
15
17
19
21
days in 2003
Low Simulated
High Simulated
Low Observed
High Observed


2002-2004
a.
Simulated
Observed
$\Delta^{14}CO_2$ (‰)
700
600
500
400
300
200
100
0
East
Low High
West
Low High
East
Low High
West
Low High
East
Low High
West
Low High
Total Soil Respiration
Litter Respiration
Mineral Soil Respiration


2001
b.
Simulated
Observed
$\Delta^{14}CO_2$ (‰)
900
800
700
600
500
400
300
200
100
0
East
High
West
Low
West
High
East
High
West
Low
West
High
Humus Respiration
Surface Litter Respiration


East High
a.
East Low
b.
West High
c.
West Low
d.
Mineral Soil Δ14C (‰)
140
130
120
110
100
90
80
180
160
140
120
100
80
1994
1996
1998
2000
2002
2004
2006
2008
Minus
Plus
Control


East High
a.
East Low
b.
West High
c.
West Low
d.
Mineral Soil Δ14C (‰)
160
140
120
100
80
180
1994
1996
1998
2000
2002
2004
2006
2008
40%
55%
47%

DISCLAIMER