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1 **A new approach to estimate fine root**
2 **production, mortality, and decomposition**
3 **using litter bag experiments and soil core**
4 **techniques**

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13

14 Abstract.

15 Aims: A new approach is proposed to estimate fine root production, mortality, and decomposition
16 that occur simultaneously in terrestrial ecosystems utilizing sequential soil core sampling or
17 ingrowth core techniques.

18

19 Methods: The calculation assumes knowledge of the decomposition rate of dead fine roots during
20 a given time period from a litter bag experiment. A mass balance model of organic matter
21 derived from live fine roots is applied with an assumption about fine root mortality and
22 decomposition to estimate decomposed dead fine roots from variables that can be quantified.

23

24 Results: Comparison of the estimated fine root dynamics with the decision matrix method and
25 three new methods (forward estimate, continuous inflow estimate, and backward estimate) in a ca.
26 80-year-old *Chamaecyparis obtusa* plantation in central Japan showed that the decision matrix
27 nearly always underestimated production, mortality, and decomposition by underscoring the
28 values of the forward estimate, which theoretically underestimates the true value. The fine root
29 production and mortality obtained by the decision matrix were on average 14% and 38% lower
30 than those calculated by the continuous inflow estimate method. In addition, the values by the
31 continuous inflow estimate method were always between those calculated by the forward estimate
32 and backward estimate methods. The latter is known to overestimate the true value.

33

34 Conclusions: Therefore, we consider that the continuous inflow estimate method provides the best
35 estimates of fine root production, mortality, and decomposition among the four approaches
36 compared.

37

38 *Key words: continuous inflow estimate, decision matrix, decomposition, fine*
39 *roots, litter bag, mortality, production*

40

41 **Introduction**

42 Terrestrial ecosystems interact with the atmosphere by affecting its carbon dioxide
43 concentration (Fung et al. 1983; Heimann et al. 1989). Therefore, good quantitative
44 knowledge of terrestrial carbon dynamics is necessary to understand potential changes in
45 the earth's climate system (Cox et al. 2000; Melillo et al. 2002; Heimann and Reichstein
46 2008). Translocation of assimilates to belowground organs of plants in terrestrial
47 ecosystems in order to grow fine roots and to support mycorrhizae is an important part of
48 net primary production (NPP). In fact, the proportion of total annual NPP allocated to
49 the belowground production may be more than 50% in some forests (Vogt et al. 1996)
50 and even more in boreal ecosystems in cold climates (Osawa et al. 2010). However, the
51 contribution of fine roots has not been fully incorporated into the estimates of NPP in
52 natural ecosystems (Hendrick and Pregitzer 1993; Lopez et al. 2001) because of the
53 difficulty of accurately measuring its pools and fluxes using available tools and
54 approaches.

55 Various methods have been developed for estimating the dynamics of fine roots in
56 natural ecosystems. Major methods include sequential soil core (Persson 1980; Ostonen
57 et al. 2005), ingrowth core (Finér et al. 1997; Ostonen et al. 2005), minirhizotron
58 (Hendrick and Pregitzer 1993; Majdi and Óhrvik 2004), nitrogen budget (Nadelhoffer et
59 al. 1985), and ecosystem carbon balance (Ågren et al. 1980), among others. Sequential
60 soil core and ingrowth core methods utilize several different approaches to calculate
61 production, mortality, and decomposition using changes in the pools of live and/or dead
62 fine roots (Vogt et al. 1998; Hendricks et al. 2006). Several in-depth comparisons (Neill
63 1992; Majdi 1996; Hertel and Leuschner 2002; Ostonen et al. 2005; Hendricks et al.
64 2006) and reviews (Vogt et al. 1996, 1998; Gill and Jackson 2000; Majdi et al. 2005;
65 Noguchi et al. 2007) of these methods have been published. Despite these publications,
66 there is still no consensus among belowground researchers on what methods most
67 realistically reflect changing carbon pools in the belowground part of the ecosystem.

68 Currently, root scientists generally agree that simultaneous fine root growth and
69 mortality cannot be measured directly with the sequential soil core and ingrowth core
70 methods (Kurz and Kimmins 1987; Santantonio and Grace 1987; Majdi 1996; Majdi et al.
71 2005). The minirhizotron technique could allow measurement of production and
72 mortality simultaneously (Hendrick and Pregitzer 1993; Steele et al. 1997; Ruess et al.
73 2003) but it has limitations (Majdi 1996; Dannoura et al. 2008). A method of

74 calculating fine root dynamics with the decision matrix was proposed for sequential soil
75 core and ingrowth core methods (McClaugherty et al. 1982; Fairley and Alexander 1985).
76 Various versions exist and have been widely used (e.g. Hertel and Leuschner 2002;
77 Ostonen et al. 2005; Hishi and Takeda 2005; Kaye et al. 2005; Hendricks et al. 2006;
78 Konôpka et al. 2006, 2007; Jourdan et al. 2008; Xiao et al. 2008; Hertel et al. 2009;
79 Jiménez et al. 2009; Murach et al. 2009; Mei et al. 2010; Yang et al. 2010). The
80 decision matrix could estimate the changing values of fine root production, mortality, and
81 decomposition, but it has a serious disadvantage. The problem is summarized in the
82 following discussion.

83 The decision matrix provides a method to estimate fine root production, mortality,
84 and decomposition during a given period, as illustrated in Table 1 (Fairley and Alexander
85 1985). For example, if ΔB and ΔN are defined as changes in fine root biomass and
86 necromass between two observations, and if both of these quantities have positive values,
87 fine root production (g) during this period is $\Delta B + \Delta N$. Mortality (m) is ΔN . Note that
88 decomposition (d) was assumed as zero. In contrast, if $\Delta B \geq 0$, but $\Delta N < 0$, then $g = \Delta B$
89 and $d = -\Delta N$, under an assumption of $m = 0$. Values of g , m , and d for other
90 combinations of ΔB and ΔN values are calculated accordingly (Table 1). The decision
91 matrix has two notable characteristics. First, fine root production (g), mortality (m), and
92 decomposition (d) are calculated from knowledge of the changes in the pools of fine root
93 biomass (ΔB) and necromass (ΔN) but without knowledge of decomposition (d) or its
94 rate. Second, some assumptions used for the calculation of g , m , and d are intuitively
95 understandable; specifically that $d = 0$ for a condition of $\Delta B \geq 0$ and $\Delta N \geq 0$. However, it
96 is also clear that decomposition may or may not be zero in this case. Assumptions for
97 other conditions are also neither immediately clear nor acceptable. In reality, the mass
98 balance of ΔB and ΔN with mass flux of g , m , and d should lead to a relationship: $g = \Delta B$
99 $+ \Delta N + d$ and $m = \Delta N + d$ (explained fully in the next section) with non-negative values
100 of g , m , and d . Therefore, the decision matrix only provides underestimates of the
101 variables of interest because production, mortality, or decomposition must be ignored in
102 specific calculations (Fairley and Alexander 1985). The discrepancy between the true
103 value and the calculation by the decision matrix is unknown due to lack of information
104 about concurrently occurring decomposition. Therefore, a more coherent approach is
105 desirable.

106 Santantonio and Grace (1987) proposed a modeling approach where the fine root
107 dynamics were evaluated by mass balance equations similar to those assumed in the
108 development of the decision matrix (McClaugherty et al. 1982; Fairley and Alexander
109 1985). The advantage of Santantonio and Grace's (1987) approach is the evaluation of
110 mortality and decomposition through modeling of the decay coefficient for dead fine
111 roots as a function of soil temperature, temperature coefficient, and reference rate of fine

112 root decomposition (their Equation 11). However, this approach (Santantonio and Grace
113 1987) has not been readily utilized by researchers because it demanded additional
114 measurement, estimation, and modeling of variables other than the decay coefficient itself
115 (Vogt et al. 1998).

116 The purpose of the present study is to propose a coherent and more practical approach
117 for estimating fine root production, mortality, and decomposition that occur
118 simultaneously. First, the fine root mass balance equations are solved mathematically
119 with acceptable assumptions for the instantaneous rates of fine root mortality and
120 decomposition. Then, fine root production, mortality, and decomposition are estimated
121 from the changes in fine root biomass and necromass, and the decomposition ratio of
122 dead fine roots during a measurement interval. The first two variables are provided by
123 either sequential soil core measurements or ingrowth core experiments. An estimate of
124 the third variable (decomposition ratio of dead fine roots) is also necessary. We show
125 that the complex modeling of the decay coefficient in Santantonio and Grace's (1987)
126 method can be replaced by a simple fine root litter bag experiment. In the estimation of
127 fine root mortality and decomposition with ordinary soil core techniques, none of the
128 methods, except for Santantonio and Grace's (1987) approach could take into account
129 simultaneous changes of these variables during a sampling interval. The present study
130 proposes a new equation that can be used to calculate these variables. We will compare
131 the estimated values between the decision matrix and the new methods that we describe.
132 In this study, fine root production is defined as the total amount of fine root ingrowth
133 during a specified period. This is conceptually similar to NPP of aboveground organs
134 and is approximately equivalent to what is often referred to as "belowground NPP".

135

136 **A mass balance model and rational for field** 137 **measurement**

138 Santantonio and Grace's model (1987) suggests that if the sequential soil core or
139 ingrowth core method is combined with an additional field experiment to assess fine root
140 decomposition, we could estimate fine root production, mortality, and decomposition that
141 occur simultaneously in a given ecosystem. As in Santantonio and Grace (1987), we
142 assume a simple mass balance model with compartments and flow of organic matter of
143 fine root origin during a discrete time interval. We then estimate the flow and change in
144 stock of organic matter during this interval.

145 Let us first consider a volume of soil in a natural ecosystem consisting of mineral soil,
146 fine roots, and organic matter derived entirely from fine roots. The organic matter

147 originating from aboveground organs is ignored. This volume of soil contains a certain
 148 amount of live fine roots at time i (denoted as B_i) and dead organic matter of fine root
 149 origin (N_i). Hereafter, the former is called fine root biomass and the latter fine root
 150 necromass. The fine root biomass and necromass change at time j (where $j > i$) to B_j and
 151 N_j due to new growth of fine roots into the soil volume, their mortality, and their
 152 decomposition. If g_{ij} and m_{ij} denote fine root production and mortality into or within the
 153 soil volume between the times i and j (Fig. 1), the change in fine root biomass (ΔB)
 154 satisfies the following mass balance equation: $\Delta B = B_j - B_i = g_{ij} - m_{ij}$. Similarly, the
 155 change in fine root necromass (ΔN ; Fig. 1) satisfies the following: $\Delta N =$
 156 $N_j - N_i = m_{ij} - d_{ij}$, where d_{ij} is decomposition of fine root necromass between i and j .
 157 Therefore, these mass balance equations suggest that the fine root production and
 158 mortality are calculated as,

$$159 \quad g_{ij} = \Delta B + \Delta N + d_{ij} \quad (1)$$

$$160 \quad m_{ij} = \Delta N + d_{ij} \quad (2)$$

161 where all terms have the dimension $\text{g m}^{-2} \Delta t \text{ d}^{-1}$ and $\Delta t = j - i$ in the following
 162 discussion. These relationships can be applied with periodic soil sampling and a root
 163 litter bag experiment to estimate fine root production, mortality, and decomposition of a
 164 given site simultaneously.

165

166 **Periodic soil sampling**

167 Soil cores of a specified diameter and volume are collected at different times, either by
 168 harvesting natural soils or by recovering fine root ingrowth cores that were installed at the
 169 beginning of the experiment at time 0. The first set of cores is collected at time i ($0 < i$;
 170 Fig. 2) for measurement of fine root biomass and necromass in the soil volume. The
 171 second set is collected later at time j ($i < j$; Fig. 2). The interval between the two
 172 collections is generally several weeks to a few months. Fine root biomass and
 173 necromass are also measured in the second set of soil cores. Here we assume that the
 174 two sets of cores sampled at times i and j have the same initial condition and are left
 175 under the same environment. Consequently, the patterns of fine root production,
 176 mortality, and decomposition are considered identical between them. In other words, we
 177 assume that fine root biomass and necromass at time i will be the same for the two sets.
 178 In reality, there will be variations in the observed values among the cores of the same set.
 179 However, we assume that the mean values are the same for the same variable at the same
 180 time of observation when the growing conditions are identical.

181

182 **Root litter bag experiment**

183 Litter bags are used to evaluate the decomposition ratio of dead fine roots. The fine root
184 litter bags containing a known amount of dead fine roots are set in the soil horizon at time
185 i . The dead fine roots are denoted as N_i^C , where the superscript C represents a value
186 obtained from the litter bags (See Litter bag C in Fig. 2). The litter bags are recovered at
187 time j (Fig. 2) for evaluating the decomposition ratio of fine root necromass. As there
188 were no live fine roots in the litter bag when they were set in the soil, we also have
189 condition $B_i^C = 0$. If fine root production between times i and j is zero, by artificially
190 excluding fine root growth into the litter bag, the fine root biomass at time j will also be
191 zero. Therefore, Equation 1 reduces to $d_{ij}^C = N_i^C - N_j^C$ from which decomposition
192 of fine root necromass can be estimated. Where γ_{ij} is the decomposition ratio
193 (dimensionless) of fine root necromass between times i and j , then

$$194 \quad \gamma_{ij} = d_{ij}^C / N_i^C = 1 - N_j^C / N_i^C \quad (3).$$

195 Decomposition of naturally dead fine roots and artificially severed live fine root segments
196 may represent different phenomena (Publicover and Vogt 1993). However, severed
197 roots are often used in decomposition experiments, as is the case in the present study.
198 Publicover and Vogt (1993) discuss possible variations and mechanisms of
199 decomposition in roots of varying origins.

201 **Calculating decomposition of dead fine roots**

202 A realistic estimate of fine root decomposition between times i and j may be obtained by
203 assuming that the fine roots die continuously at a constant instantaneous mortality of σ
204 ($\text{g m}^{-2} \text{d}^{-1}$) and disappear at an instantaneous decomposition of $\gamma \cdot N$ ($\text{g m}^{-2} \text{d}^{-1}$) with a
205 constant decomposition rate γ (d^{-1}), where σ and γ are formally defined as

$$206 \quad m_{ij} = \int_i^j \sigma dt \quad \text{and} \quad d_{ij} = \int_i^j \gamma \cdot N dt, \quad \text{and } N \text{ is fine root necromass at time } t (i \leq t \leq j).$$

207 These assumptions are identical to those used by Santantonio and Grace (1987). The
208 assumption of constant root mortality, σ , must be introduced due to lack of sufficient
209 knowledge about its behavior but it can vary for different observation intervals. Given
210 these assumptions, the instantaneous necromass mass balance can be expressed as
211 $dN/dt = -\gamma \cdot N + \sigma$. This is a linear first-order differential equation (Kreyszig 1972),
212 and solving for N yields $N = \sigma / \gamma + (N_i - \sigma / \gamma) \cdot e^{-\gamma \cdot (t-i)}$. By applying this

213 relationship to the present situation, we obtain an expression for fine root decomposition
214 between times i and j as (see Appendix for derivation)

$$215 \quad d_{ij} = -\Delta N - (\Delta N / \gamma_{ij} + N_i) \cdot \ln(1 - \gamma_{ij}) \quad (4),$$

216 where, γ_{ij} is as defined in Equation 3. Therefore, the amount of the decomposed dead
217 fine roots can be estimated from three variables (ΔN , N_i , and γ_{ij}) that can be measured
218 by soil sampling and a relatively simple experiment. The modeling exercise
219 (Santantonio and Grace 1987) is no longer required. The estimate of d_{ij} from Equation 4
220 may be referred to as the continuous inflow estimate. Comparison of Equations 2 and 4
221 yields

$$222 \quad m_{ij} = -(\Delta N / \gamma_{ij} + N_i) \cdot \ln(1 - \gamma_{ij}) \quad (5).$$

223 An estimate of fine root mortality (σ), which was assumed to be constant during a
224 measurement period can be calculated as $m_{ij}/\Delta t$. Note that mortality is expressed neither
225 by ΔN nor ΔB alone as in the decision matrix. In this new approach, the decomposition
226 ratio (γ_{ij}) is also related to mortality.

227 Decomposition of fine root necromass between times i and j (d_{ij}) can also be
228 approximated as the estimated decomposition ratio multiplied by the fine root necromass
229 at time i

$$230 \quad d_{ij} = \gamma_{ij} \cdot N_i \quad (6).$$

231 This expression (forward estimate) assumes that decomposition occurring between times i
232 and j originates from the necromass present at time i and that there is neither fine root
233 mortality nor associated decomposition of the newly dead fine roots between i and j (in
234 order to calculate the amount of decomposition). Therefore, the decomposition
235 estimated with Equation 6 is an underestimate.

236 Alternatively, if N_j , necromass at time j through decomposition of dead fine roots
237 between times i and j with a decomposition ratio of γ_{ij} , is known, but N_i , necromass at
238 time i, is not known, fine root decomposition can also be estimated (backward estimate)
239 as

$$240 \quad d_{ij} = \gamma_{ij} \cdot N_j / (1 - \gamma_{ij}) \quad (7).$$

241 This representation means that new dead fine roots may be added between times i and j,
242 all of which will occur as a pulse immediately after time i. However, in reality, fine root
243 mortality can occur anytime between i and j, which makes the residence time of these
244 newly dead fine roots shorter than j-i. Therefore, the decomposition estimate from
245 Equation 7 will be an overestimate. These considerations suggest that the true value of
246 fine root decomposition lies between the values calculated by Equations 6 and 7 and the
247 values will coincide only when there is no fine root mortality between times i and j.

248 Therefore, the estimate of d_{ij} from Equation 4 may be considered the most realistic
249 theoretical value among the values calculated by Equations 4, 6, and 7.

250 Fine root production (g_{ij}) and mortality (m_{ij}) are then calculated by Equations 1
251 and 2. Estimation using these relationships is practical. It is also expected to be
252 applicable in many types of terrestrial ecosystems for varying amounts of production,
253 mortality, and decomposition. The ability of the present approach to detect changes in
254 fine root biomass and necromass pools is the same as that of the methods proposed earlier
255 (e.g., decision matrix). However, the treatment of decomposition is different. The
256 present approach takes into account decomposition directly, whereas the decision matrix
257 in effect ignores decomposition, leading to underestimation when decomposition is not
258 negligible.

259

260 **Materials and methods**

261 **Study site**

262 The proposed method of estimating fine root production, mortality, and decomposition
263 was applied to a ca. 80-year-old plantation of *Chamaecyparis obtusa* Endl. (Hinoki
264 cypress) at Ryukoku Forest, Ohtsu, Japan, at 34°58'N, 135°56'E. The elevation of the
265 stand is 130 m above sea level. The soil of the study area is characterized by sand and
266 small round gravel stones, and is classified as yellowish brown forest soil derived from
267 lacustrine sediments of Cenozoic origin belonging to the Kobiwako Group (Ministry of
268 Land, Infrastructure, Transportation and Tourism 1982). The Ryukoku Forest is a
269 secondary forest of mainly canopy trees of *Quercus serrata* Thunb. and *Pinus densiflora*
270 Sieb. et Zucc. that used to be managed communally. The forest supplied agricultural
271 fertilizer and wood material for local farmers, but now the area is abandoned. The *C.*
272 *obtusa* stand has not been managed for at least 40 years (Miyaura 2009) and shows signs
273 of active self-thinning (Osawa and Allen 1993). The stand is about 800 m² with stem
274 density, mean stem diameter at breast height, canopy tree height, and basal area of *C.*
275 *obtusa* at 1175 ha⁻¹, 22 cm, 20 m, and 51 m²/ha, respectively (Tago J *unpublished data*).
276 In addition, the stand also has some canopy and subcanopy trees of *Q. serrata*, *P.*
277 *densiflora*, and *Ilex pedunculosa* Miq..

278

279 **Ingrowth core experiment in 2007**

280 To assess fine root dynamics, a cylindrical tube 32 mm in diameter and 21 cm in length
281 was used as the fine root ingrowth core and the root litter bag. The cylindrical tube is
282 made of plastic mesh with approximately 3 mm mesh openings and a mesh bottom made
283 of the same material as the cylinder wall. This cylinder was filled with soil from the
284 study site, but all live roots, dead roots, and decomposing organic matter (diameter $\phi >$
285 0.5 mm) were removed by washing the soil ten times with tap water in a container and
286 sieving the supernatant fluid with suspended organic matter through a 0.5 mm mesh sieve
287 after each washing. Fine particles ($\phi \leq 0.5$ mm) of mineral soil and particulate
288 organic matter in the supernatant fluid were saved, dried at room temperature, broken into
289 shatters, and mixed with the soil sediment in the container for use in the experiment.
290 Some of the soil-filled plastic mesh cylinders were covered with a ‘root-impermeable
291 water-permeable (RIWP) sheet[®]’ (Toyobo Co., Osaka, Japan) to exclude fine roots that
292 could grow into the cylinder. The RIWP sheet has a pore size of approximately 6 μ m
293 and blocked practically all ingrowth of fine roots; however, fine particles of soil, rain
294 water, and other microorganisms could penetrate through the sheet.

295 A known mass of dead fine roots of *C. obtusa* was added to each of the RIWP sheet-
296 covered cylinders so that they acted as root litter bags. Severed live fine root segments
297 were collected, dried at room temperature, and used as dead fine roots in the litter bags in
298 this experiment (see Publicover and Vogt (1993) for caution). Soil was included in the
299 litter bags to improve the physical contact of the soil particles with the inserted dead
300 roots; however, use of ordinary litter bags without soil is a possible alternative. In total,
301 60 soil cylinders were prepared; 30 of which were covered with the RIWP sheet. The
302 tops of all cylinders were covered with thin translucent fabric to exclude input of
303 aboveground litter.

304 Six sampling lines, approximately 30 m long, were established in the stand. They
305 were parallel to one another and about two-meters apart. The ground surface along the
306 sampling lines was marked at one-meter intervals to indicate locations for the soil
307 cylinders. The sampling points for the 30 soil cylinders (fine root ingrowth cores) and
308 the 30 root litter bag cores were selected randomly. The 30 ingrowth cores were buried
309 singly in early July 2007 after coring the ground with a stainless steel tube 38 mm in
310 diameter and 45 cm in length by pounding it 20 cm into the ground. The narrow space
311 between the ingrowth core and the inner wall of the cored hole was filled with the same
312 soil as that used to fill the ingrowth core.

313 In mid-August 2007, six ingrowth cores were chosen randomly, taken out of the
314 ground by creating 20-cm deep incisions around the core with a knife and the ingrowth

315 core was pulled out by hand. These six ingrowth cores correspond to Core A in Fig. 2.
316 At the same time, six root litter bag cores were established at randomly selected locations
317 among the remaining sampling points (corresponding to Litter bag C in Fig. 2). Six
318 weeks later, these six litter bag cores and another set of six randomly selected regular
319 ingrowth cores (Core B in Fig. 2) were recovered on the same day by a method similar to
320 the one described above. The collected soil cylinders were brought to the laboratory.
321 The contained soil was washed using the same method applied in preparation of the soil
322 material. Then the recovered organic material was sorted into live fine roots, dead fine
323 roots, and other organic matter. The live and dead fine roots were differentiated by their
324 color and resilience (Hishi and Takeda 2005; Konôpka et al. 2006) because more exact
325 methods were not practical in field studies. The roots of different tree species were not
326 distinguished in the present study; however, most were from *C. obtusa*. They were
327 dried in a forced air oven at 80°C for 48 hours, and biomass and necromass were
328 measured separately. The mass of the live fine roots was considered fine root biomass,
329 and the mass of the dead fine roots combined with other organic matter ($\phi > 0.5$ mm)
330 was regarded as necromass.

331 Each time the soil cylinders corresponding to Core B and Litter bag C were
332 recovered, another set of six root litter bag cores was buried at randomly selected
333 sampling points. They were taken out of the ground on the next sampling occasion (new
334 Litter bag C; generally six weeks later) along with a set of six randomly selected fine root
335 ingrowth cores (new Core B). Core B from the previous sampling time becomes the
336 new Core A. Analysis of these cores gave the biomass and necromass values at the
337 experiment's next time step. By repeating this process, fine root production, mortality,
338 and decomposition were estimated until December 2007, generally at six-week intervals.
339 In addition, six root litter bags were set, using a method similar to that employed initially,
340 and were recovered in mid-August so that the fine root decomposition ratio during the
341 first period could also be estimated.

342

343 **Sequential soil core sampling in 2010**

344 Soil cores were sampled sequentially with the same stainless steel tube at randomly
345 selected points, generally at nine-week intervals between June 22 and December 16,
346 2010. The potential sampling points were located at one-meter intervals along the
347 sampling lines in the same *C. obtusa* stand. Usually three cores were collected at each
348 sampling. Root litter bags of the same construction as the 2007 experiment were
349 prepared and buried each time soil samples were collected. The root litter bag cores
350 recovered at each sampling was generally three. The collected soil cylinders and

351 contents of the root litter bag cores were washed in tap water applying the same method
352 used in the 2007 experiment. Then, after oven-drying at 80°C for 48 hours, live fine
353 roots, dead fine roots, and other organic matter ($\phi > 0.5$ mm) were quantified. Only
354 the mass of dead fine roots was regarded as necromass in the 2010 study because the
355 origin of decomposing organic matter was generally unknown. The stand was thinned
356 to reduce the tree density and stem volume of *C. obtusa* by 47% and 36%, respectively, in
357 March 2010 (Tago J *personal communication*) for a separate study of forest growth prior
358 to the start of the present soil core sampling, which commenced on June 22, 2010.
359

360 **Mass flux calculation and statistical analysis**

361 The measured values of fine root biomass and necromass in each soil core, ingrowth core,
362 and root litter bag were divided by the area of the inner cross-section of the stainless steel
363 pipe (0.00101 m² for soil core) or of the ingrowth core and root litter bag (0.000706 m²)
364 to obtain the mass per square meter of the ground. Then, they were divided by the
365 duration of each experiment in days ($\Delta t = j - i$) to calculate the mass flux in g m⁻² d⁻¹.
366 The 95% confidence limits of the estimated means were calculated by the bootstrap
367 method with bias-corrected percentile approach by randomly sampling a set of mass data
368 n times with replacement (when sample size is n) to obtain the means, then repeating the
369 process 1,000 times to generate the 95% confidence interval (CI) (Efron 1979; Efron and
370 Gong 1983). Decomposition is calculated from a relatively complex equation (Equation
371 4), making use of traditional statistical inference inappropriate. Therefore, significant
372 differences in the means of biomass or necromass (Hendricks et al. 2006) were not
373 applied to calculate production, mortality, and decomposition in the present study, except
374 for comparisons in Table 2.

375 The following is an example of the mass flux calculation. Data collected on October
376 11 and November 10, 2007 (55 days apart) are used. The fine root necromass in the root
377 litter bag core was 0.739 g on October 11. On November 10, it was 0.482 g.
378 Therefore, the root decomposition ratio during this period (γ_{ij}) was 0.347 (Equation 3).
379 The mean values of fine root biomass and necromass per core were 0.0101 g and 0.0259
380 g, respectively, on October 11. These values changed to 0.165 g and 0.0439 g,
381 respectively, on November 10. Therefore, $\Delta B = 0.165 - 0.0101 = 0.154$ g and $\Delta N =$
382 $0.0439 - 0.0259 = 0.0180$ g per core. Fine root decomposition during this period will be
383 calculated by Equation 4 as $d_{ij} = -0.018 - (0.018/0.347 + 0.0259)\ln(1 - 0.347) = 0.015$ (g
384 per core per 55 days). Then fine root mortality (m) and production (g) become $m =$
385 $0.018 + 0.015 = 0.033$ and $g = 0.154 + 0.018 + 0.015 = 0.187$ (g per core per 55 days;

386 Equations 2 and 1). The results of calculation can be translated to $d = 0.392$, $m = 0.855$,
387 and $g = 4.849$ ($\text{g m}^{-2} \text{d}^{-1}$).
388

389 Results

390 Ingrowth core experiment in 2007

391 Based on the continuous inflow estimate (Equation 4), the observed decomposition, d_{ij} ,
392 ranged between 0.14 and 0.76 $\text{g m}^{-2} \text{d}^{-1}$ and showed little seasonal variation (black
393 pattern in Figs. 3a-3d). Values of fine root mortality, m_{ij} , ranged between 0.85 and 1.57
394 $\text{g m}^{-2} \text{d}^{-1}$. The mortality was relatively low during summer and fall, and increased
395 during winter between November and December (black pattern in Figs. 3e-3h).
396 Seasonal dynamics of fine root production, g_{ij} , showed a different pattern. It was low in
397 the summer (August value was 1.42 $\text{g m}^{-2} \text{d}^{-1}$), peaked in October at 4.84 $\text{g m}^{-2} \text{d}^{-1}$, and
398 became nearly zero through November and December in the continuous inflow model
399 (black pattern in Figs. 3i-3l). The bootstrap 95% CI of the estimated fine root
400 production was large, mostly due to the small sample size (generally six) and propagation
401 of errors associated with the measurement of m_{ij} and d_{ij} (see Equations 1, 2, 4, and 5).
402 Due to the large 95% CI, fine root production was not distinguishable from zero in
403 November and December (Figs. 3k and 3l).

404 The calculated values of fine root production, mortality, and decomposition by the
405 forward estimate (Equation 6) were lower than those estimated by the continuous inflow
406 assumption (Equation 4). On average, the values were 47% lower for decomposition
407 (Figs. 3a-3d), 15% lower for mortality (Figs. 3e-3h), and 7% lower for production (Figs.
408 3i-3l). On the other hand, the values calculated by the backward estimate (Equation 7)
409 were always higher than the continuous inflow estimate. They were higher on average
410 by 59% for decomposition (Figs. 3a-3d), 18% for mortality (Figs. 3e-3h), and 8% for
411 production (Figs. 3i-3l). The fine root production calculated by the forward estimate
412 and the continuous inflow assumption were negative during the fourth period (ending on
413 December 21; Fig. 3l); however, because negative values are ecologically unacceptable,
414 we assigned zero to them. The reason for the negative production is the non-closure of
415 mass balance with all non-negative terms in Equation 1.

416 The estimates of fine root decomposition by the decision matrix were zero for the first
417 three periods until November 10 (Figs. 3a-3c). In contrast, the decomposition estimates
418 by the forward, continuous inflow, and backward models were generally positive. The
419 pattern differed in the fourth period (ending on December 21) where the decision matrix
420 decomposition estimate was greater than both the forward and continuous inflow

421 estimates (Fig. 3d). On average, fine root decomposition estimated by the decision
422 matrix was 69% lower than that calculated by the continuous inflow assumption.

423 Relationships among the mortality values calculated by the decision matrix and by the
424 forward, continuous inflow, and backward models (Figs. 3e-3h) are similar to those
425 observed for fine root decomposition. The mortality values estimated by the decision
426 matrix were on average 31% lower than those calculated by the continuous inflow
427 assumption. The decision matrix also returned the lowest fine root production values
428 when the four approaches were compared (Figs. 3i-3l). The decision matrix production
429 estimates were on average 18% lower than the continuous inflow estimates.

430

431 **Sequential soil core sampling in 2010**

432 Patterns of the calculated fine root decomposition, mortality, and production by the four
433 methods (decision matrix, forward estimate, continuous inflow, and backward estimate)
434 in the sequential soil core sampling for 2010 (Fig. 4) were generally similar to those
435 observed in the 2007 ingrowth core experiment (Fig. 3). The decision matrix gave the
436 lowest estimates. The values calculated by the continuous inflow model were also
437 between those predicted by the forward and backward estimates.

438 The continuous inflow model (Equation 4) returned decomposition values, d_{ij} ,
439 ranging between 0.27 and 0.42 $\text{g m}^{-2} \text{d}^{-1}$. It showed little seasonal variation, as
440 evidenced in the 2007 data (black pattern in Figs. 4a-4c). Fine root mortality, m_{ij} ,
441 ranged between 0.38 and 1.60 $\text{g m}^{-2} \text{d}^{-1}$. The mortality was somewhat high in summer
442 but decreased after August (black pattern in Figs. 4d-4f). The greatest value of fine root
443 mortality was observed during the first period (ending on August 24) at 1.60 $\text{g m}^{-2} \text{d}^{-1}$
444 (Fig. 4d). Seasonal dynamics of fine root production, g_{ij} , was relatively stable, and
445 varied only between 2.07 and 2.38 $\text{g m}^{-2} \text{d}^{-1}$ (black pattern in Figs. 4g-4i). This may
446 reflect the low fine root production at Ryukoku Forest in 2010 (Hattori 2011). The
447 bootstrap 95% CI of the estimated fine root production was large—a pattern similar to the
448 observation in 2007 (Figs. 3i-3l).

449 The fine root decomposition estimated by the decision matrix were all zero, but
450 other methods predicted positive values (Figs. 4a-4c). Mortality estimated by the
451 decision matrix were on average 47% lower than that calculated by the continuous inflow
452 assumption. The decision matrix also led to the lowest fine root production estimates
453 when the four approaches were compared (Figs. 4g-4i). The production estimates from
454 the decision matrix were on average 15% lower than the continuous inflow estimates.

455

456 Discussion

457 Some previous studies reported that simultaneously varying fine root production,
458 mortality, and decomposition cannot be measured directly with sequential soil core or
459 ingrowth core methods (Kurz and Kimmins 1987; Santantonio and Grace 1987; Majdi
460 1996; Majdi et al. 2005); however, such measurement is possible with the addition of
461 litter bags as we have described in the present study.

462 Our results showed that the decision matrix nearly always gave values lower than
463 those calculated by the forward estimate (Figs. 3 and 4), which in itself is an
464 underestimate. This was because increments of both fine root biomass and necromass
465 were positive at nearly all periods, which forced the calculation of fine root
466 decomposition by the decision matrix to zero (Fairley and Alexander 1985), although
467 there were appreciable amounts of decomposition according to the other methods. In
468 one case, the decision matrix estimates were greater than those of other methods (Figs. 3d
469 and 3h). However, this is an anomaly created by non-closure of mass balance in fine
470 root dynamics due to the measurement error. Theoretically, the calculations by the
471 decision matrix are nearly always underestimates, and consequently cannot be regarded
472 as the best method.

473 The forward estimate is also bound to be an underestimate, because it only takes into
474 account decomposition of dead fine roots present at the beginning of the period
475 considered. It ignores decomposition of new roots that died during the measurement
476 period. On the other hand, the backward estimate will be an overestimate because it
477 assumes that death of new roots during the period occurs at one time immediately
478 following the start of the period under consideration. Therefore, the true value of
479 decomposition must lie between the values calculated by the forward and backward
480 estimates. The continuous inflow estimate consistently satisfies this condition (Figs. 3
481 and 4).

482 Another characteristic of the present examples of continuous inflow estimates is that
483 the magnitude of 95% CI tends to be large for fine root production (Figs. 3 and 4). This
484 is mainly due to the propagation of measurement errors in the calculation which involves
485 several variables (Equations 1 and 4) each of which contain variations. Propagation of
486 measurement error is a problem that cannot be avoided when several measurements are
487 added to derive a production estimate. There are mainly two sources of error. One is
488 addition of increments in biomass and necromass and decomposition during a single
489 measurement period (Equation 1). Each of these terms has its own variation, which
490 must be added to obtain that of production. The other source of error comes from
491 addition of production values for different measurement periods. Use of only the
492 significant differences will reduce the propagated error by omitting variation in non-

493 significant data; however, it cannot be free of error propagation as long as addition of
494 terms is involved. A relatively large sample size will be necessary to improve accuracy
495 substantially and the necessary sample size is likely to vary depending on plant species
496 and site conditions.

497 However, if the purpose of the study is to assess the magnitude of NPP or the
498 contribution of fine root production in total NPP, a continuous inflow estimate will be
499 more desirable. The estimate of fine root production by the decision matrix (as
500 compared to continuous inflow model) was 14% lower on average, and 38% lower in an
501 extreme case, in the present study of the *C. obtusa* stand in 2007 and 2010. Therefore,
502 use of the decision matrix is likely to lead to substantial underestimation of NPP of the
503 ecosystem. The degree of error was even greater for fine root mortality. When
504 calculated by the decision matrix fine root mortality was 38% lower on average than the
505 value estimated by the continuous inflow assumption. In an extreme case, the decision
506 matrix estimate was 80% lower.

507 The effect of the use of different methods of calculation on fine root production over a
508 longer measurement period is also of interest. When only the significant differences of
509 biomass and necromass between measurement periods (ΔB and ΔN) were added, decision
510 matrix led to an estimate of $256 \text{ g m}^{-2} 166\text{d}^{-1}$ for the 2007 experiment. In contrast, the
511 decision matrix suggested $333 \text{ g m}^{-2} 166\text{d}^{-1}$ when all ΔB and ΔN values were used for
512 calculation regardless of their significance (Table 2). We also obtained production of
513 $304 \text{ g m}^{-2} 166\text{d}^{-1}$ when only the first and last sampling data were used to calculate
514 $\Delta B + \Delta N$ (Table 2). The last calculation is identical to the estimate by the decision
515 matrix using the same two observations (Table 2), and is clearly an underestimate since
516 decomposition is ignored (Equation 1). When we use the same observations, but take
517 into account decomposition calculated using the mean decomposition rate (the parameter
518 γ in Equation A2) for all periods and the continuous inflow estimate, the fine root
519 production (Equation 1) becomes 392 g m^{-2} per 166 d (Table 2). Use of only significant
520 differences has been the method to avoid overestimation; however, it resulted in
521 substantial underestimation ($256 \text{ g m}^{-2} 166\text{d}^{-1}$) when combined with the decision matrix.
522 This value was 15% smaller than the known underestimate of $304 \text{ g m}^{-2} 166\text{d}^{-1}$. It was
523 also 34% smaller than the continuous inflow estimate ($392 \text{ g m}^{-2} 166\text{d}^{-1}$) calculated with
524 the first and last sampling data (Table 2).

525 Patterns of the estimated production were similar for the 2010 experiment. Decision
526 matrix with data from all periods resulted in underestimation of $493 \text{ g m}^{-2} 177\text{d}^{-1}$ since
527 this value was equal to the estimate of $\Delta B + \Delta N$ calculated by using only the first and last
528 sampling data without decomposition (Table 2). Another characteristic of the 2010 data
529 is that the estimates calculated only with the significant differences resulted in unusually

530 low values. This was because all differences in fine root biomass and necromass were
531 not significantly different between the measurement periods.

532 These observations and results of Table 2 suggest that use of only the significant
533 differences tends to substantially underestimate fine root production, particularly when
534 the decision matrix was used for calculation. Forward estimate also led to values lower
535 than the known underestimate of $\Delta B + \Delta N$ in the majority of cases. On the other hand,
536 the continuous inflow estimate suggested stable production values regardless of the
537 number of measurement periods applied.

538 The decomposition rates of fine root necromass that we observed in the present study
539 are probably reasonable. The decomposition rates (γ ; evaluated with Equation A2)
540 were 0.0071 ± 0.0014 (d^{-1}) for a series of ca. six-week-long experiments in 2007. They
541 are equivalent to annual rates of 2.61 ± 0.53 (y^{-1} ; Table 3). These are also translated as
542 monthly values of the decomposition ratio (γ_{ij}) at 0.19 ± 0.03 (dimensionless), or annual
543 values of 0.87 ± 0.07 (dimensionless; Table 3) for a hypothetical condition that assumes
544 the rate does not change for an entire year (e.g., Equation A2). Similarly, the
545 decomposition rates (γ) for the 2010 sequential soil cores were 0.0035 ± 0.0007 (d^{-1}) for
546 ca. two-month observation periods. They are equivalent to annual rates of 1.30 ± 0.28
547 (y^{-1}). They correspond to monthly rates γ_{ij} of 0.10 ± 0.01 (dimensionless), or annual
548 values of 0.65 ± 0.05 . Therefore, the decomposition rates of dead fine roots observed in
549 the present study are generally of similar magnitude to those assumed by Publicover and
550 Vogt (1993) in their simulation: monthly γ_{ij} of 0.15 or annual γ_{ij} of 0.85 (Table 3).

551 Comparison of annual decomposition rates (γ) among various ecosystems, presented
552 in Table 3 indicates that the estimates for the *C. obtusa* forest in the present study are
553 somewhat higher than those reported for other ecosystems. It is also noted that the
554 various ranges of decomposition rates are similar regardless of the methods used for
555 estimation. For example, when the method used in the present study was applied, the
556 annual γ was 0.16 for an old jack pine stand in Canada. This value is nearly equal to
557 the global mean for a conifer forest when regular envelope-type litter bags are used
558 (Table 3). Therefore, variation in observed decomposition rates is likely to have
559 originated primarily from differences in the characteristics of ecosystems, and not from
560 the methods used for analysis. In the present study, the annual decomposition rates were
561 extrapolated from data from field experiments that lasted 30—91 days during non-winter
562 seasons. True annual decomposition rates will be lower than those reported.

563 In summary, both sequential soil cores and ingrowth cores could be used with root
564 litter bag experiments to estimate fine root production, mortality, and decomposition
565 occurring simultaneously, and could provide those parameters with mass-based flux
566 variables (e.g., $g\ m^{-2}\ d^{-1}$). Generalized relationships were derived that allow calculation

567 of production, mortality, and decomposition from changes between observations in fine
568 root biomass and necromass, and from the decomposition ratio of dead fine roots
569 (Equations 1, 2, and 4). The decomposition estimate calculated with the continuous
570 inflow assumption (Equation 4) is considered the best among the four approaches
571 compared because it may closely represent the reality of the process of fine root
572 mortality. Accordingly, the continuous inflow approach would also be the best choice
573 for calculating fine root mortality and production (Equations 1 and 2). A large sample
574 size is necessary to reduce the 95% CI of the estimated production by the continuous
575 inflow estimate; however, it would be theoretically more appropriate than the decision
576 matrix which could not realistically take into account decomposition. Development of
577 the continuous inflow approach is significant not necessarily because it suggests values
578 different from those calculated by the decision matrix, but because it is applicable to
579 general situations regardless of the magnitude of decomposition of dead roots, root
580 mortality, and production. The decision matrix will give theoretically realistic values
581 only for situations where decomposition, mortality, or production is negligible. The
582 ability of the continuous inflow approach to estimate fine root dynamics with a simple
583 litter bag experiment is also a significant improvement over the method of Santantonio
584 and Grace (1987), in which decomposition must be estimated through relatively complex
585 modeling with additional environmental data.

586

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593

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754

755

756 Appendix

757 **Continuous inflow estimate of d_{ij} (Equation 4):** First, let us consider the decomposition
758 process of dead fine roots occurring in a root litter bag treated with the ‘root-impermeable
759 water-permeable (RIWP) sheet’ (see Materials and methods). The amount N of dead
760 fine root is assumed to decompose with instantaneous decomposition of $\gamma \cdot N$ where γ
761 is the decomposition rate. This process can be described by a differential equation,
762 $dN / dt = -\gamma \cdot N$. With a boundary condition, $N = N^C_i$ at $t = i$, this differential
763 equation is solved as

$$764 \quad N = N^C_i \cdot e^{-\gamma \cdot (t-i)} \quad (\text{A1}).$$

765 If $N = N^C_j$ at $t = j$, and $\Delta t = j - i$, Equation A1 gives, $N^C_j = N^C_i \cdot e^{-\gamma \cdot \Delta t}$.

766 This relationship and Equation 3 in the text yield an expression for the decomposition
767 ratio of fine root necromass between times i and j , γ_{ij} , as

$$768 \quad \gamma_{ij} = 1 - e^{-\gamma \cdot \Delta t} \quad (\text{A2}).$$

769 Note that γ and γ_{ij} in Equation A2 are different parameters.

770 Next, let us consider the decomposition process of dead fine roots in an ingrowth core
771 where there is both instantaneous fine root decomposition of $\gamma \cdot N$ and instantaneous
772 fine root mortality (addition of new dead roots) at a constant level of σ . Here, the
773 process can be described by a differential equation:

$$774 \quad dN / dt = \sigma - \gamma \cdot N \quad (\text{A3})$$

775 It is well known that the linear first-order differential equation of a form $dy/dx + P(x) \cdot y =$
776 $Q(x)$ with two variables x and y has a solution (Kreyszig 1972):

$$777 \quad y = e^{-\int P(x) dx} \cdot \left\{ \int_0^x Q(x) e^{\int P(x) dx} dx + C \right\} \quad (\text{A4})$$

778 where C is any constant. Therefore, Equation (A3) can be solved with a boundary
779 condition, $N = N_i$ at $t = i$, as,

$$780 \quad N = (\sigma / \gamma) + (N_i - \sigma / \gamma) e^{-\gamma \cdot (t-i)} \quad (\text{A5}).$$

781 By calculating N_j with Equation A5 for $t = j$, then inserting Equation (A2), we obtain the
 782 relationship, $\sigma / \gamma = \Delta N / \gamma_{ij} + N_i$, where $\Delta N = N_j - N_i$. Applying this
 783 relationship in Equation A5 yields,

$$784 \quad N = \Delta N \cdot (1 - e^{-\gamma \cdot (t-i)}) / \gamma_{ij} + N_i \quad (\text{A6}).$$

785 Then, by noting $\gamma \cdot \Delta t = -\ln(1 - \gamma_{ij})$ from Equation A2, the amount of decomposed
 786 dead fine roots between times i and j could be obtained from Equation A6 as,

$$787 \quad d_{ij} = \int_i^j \gamma \cdot N dt = -\Delta N - (\Delta N / \gamma_{ij} + N_i) \cdot \ln(1 - \gamma_{ij}) \quad (\text{A7}).$$

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814 **Tables**

815 Table 1 A version of the decision matrix by Fairley and Alexander (1985) for
 816 calculating production (g) and mortality (m) of fine roots and decomposition (d) of dead
 817 fine roots during a measurement interval. ΔB and ΔN represent change during a
 818 measurement interval in the pools of live fine root mass and dead fine root mass,
 819 respectively. Inequalities in the top two rows and those in the first column from the left
 820 indicate conditions on the values of ΔB and ΔN . Suggested equations for calculation of
 821 g , m , and d are given in the Table for specific combination of the values of ΔB and ΔN .
 822 The equations in parentheses are assumptions under specific conditions.

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	$\Delta B \geq 0$	$\Delta B < 0$	
		$\Delta N > \Delta B $	$ \Delta B > \Delta N$
829 $\Delta N \geq 0$	$g = \Delta B + \Delta N$	$g = \Delta B + \Delta N$	$(g = 0)$
830	$m = \Delta N$	$m = \Delta N$	$m = -\Delta B$
831	$(d = 0)$	$(d = 0)$	$d = -\Delta B - \Delta N$
833 $\Delta N < 0$	$g = \Delta B$	$(g = 0)$	$(g = 0)$
834	$(m = 0)$	$m = -\Delta B$	$m = -\Delta B$
835	$d = -\Delta N$	$d = -\Delta B - \Delta N$	$d = -\Delta B - \Delta N$

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848 Table 2 Comparison of fine root production in dry mass during the entire period of
 849 experiment estimated by various methods of calculation for the *Chamaecyparis obtusa*
 850 forest at Ryukoku Forest in 2007 and 2010. The 2007 experiment started on July 6,
 851 ended on December 21, and lasted for 166 days with four measurement periods. The
 852 2010 experiment started on June 22, ended on December 16, and lasted for 177 days with
 853 three measurement periods. Fine root ingrowth core was used in 2007 while sequential
 854 soil cores were taken in 2010, both with accompanying root decomposition experiment.
 855 Production was calculated for three groups of data that differed in characteristics. First
 856 group includes only significant differences in ΔB and ΔN ; second group consists of data
 857 of all measurement periods regardless of significance of difference; third includes only
 858 data of the first and last soil cores sampled during the experiment.

860	Method used for calculation	2007 study (g m ⁻² 166d ⁻¹)	2010 study (g m ⁻² 177d ⁻¹)
862	<hr/>		
863	<i>Using only significant differences</i>		
864	Decision matrix	256 [¶]	0 [¶]
865	Forward estimate [†]	304 [¶]	56 [¶]
866	Continuous inflow estimate [†]	330	89 [¶]
867	Backward estimate [†]	365	130 [¶]
868			
869	<i>Using data from all periods</i>		
870	Decision matrix	333	493 [¶]
871	Forward estimate	243 [¶]	538
872	Continuous inflow estimate	391	574
873	Backward estimate	408	622
874			
875	<i>Using only first and last sampling data</i>		
876	$\Delta B + \Delta N^{\ddagger}$	304[¶]	493[¶]
877	Decision matrix	304 [¶]	493 [¶]
878	Forward estimate	304 [¶]	505
879	Continuous inflow estimate	392	588
880	Backward estimate	619	744
881	<hr/>		

882 [†]Decomposition was calculated by forward, continuous inflow, or backward estimate,
 883 then significant values of ΔB and ΔN (Equation 1) were added.

884 [‡]Conservative estimate of production in boldface numerals by ignoring decomposition in
 885 Equation 1

886 [¶]Italic numerals indicate values smaller than or equal to the estimate shown with boldface
 887 numerals for each year.

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890 Table 3 Comparison of annual decomposition rate γ (y^{-1}) and annual decomposition
 891 ratio γ_{ij} of dead fine roots reported in various forest ecosystems. Equation A2 was used
 892 for the necessary conversion between γ and γ_{ij} . Mean \pm SE are indicated where
 893 appropriate. Data are categorized into four groups depending on the method used for
 894 estimation: *Litter bags (loose soil contact)* is ordinary envelope-type litter bags made of
 895 mesh cloth, *Litter bags (close soil contact)* is the root-impermeable water-permeable
 896 sheet-covered and soil-filled ingrowth core—a construction identical to that used in the
 897 present study, *Trench-plot* is a trenched soil block in which root decay is monitored, and
 898 *Simulation* indicates a value derived hypothetically for use in a simulation study.

899 Superscripts indicate references where decomposition rates or ratios were reported:

900 ^aSilver and Miya (2001), ^bCusack et al. (2009), ^cOsawa A. (unpublished data),

901 ^dPublicover (1992), ^eSilver and Vogt (1993), ^fcalculated from monthly γ_{ij} of 0.15 in

902 Publicover and Vogt (1993), and ^gsample size not applicable due to simulation.

903

904	(y^{-1})	(dimensionless)	Number of
905 Site	γ	annual γ_{ij}	estimated γ

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907 *Litter bags (loose soil contact)*

908 Global mean, broadleaf	0.44 ^a \pm 0.06	0.35	40
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909 Global mean, conifer	0.17 ^a \pm 0.02	0.15	10
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910 LUQ [†] , Puerto Rico	1.06 ^b \pm 0.28	0.65	4
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911 GSF [†] , Puerto Rico	0.42 ^b \pm 0.07	0.34	4
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913 *Litter bags (close soil contact)*

914 this study at RKF [†] , 2007	2.61 [¶] \pm 0.53	0.87 [¶] \pm 0.07	5
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915 this study at RKF [†] , 2010	1.30 [¶] \pm 0.28	0.65 [¶] \pm 0.05	4
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916 WBNP [†] , young jack pine	0.24 ^c \pm 0.03	0.21 \pm 0.02	2
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917 WBNP [†] , mid-age jack pine	0.30 ^c \pm 0.05	0.26 \pm 0.03	5
---	------------------------------	-----------------	---

918 WBNP [†] , old jack pine	0.16 ^c \pm 0.04	0.14 \pm 0.04	5
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919

920 *Trench-plot*

921 NJPB [†] , pine	0.58 ^d	0.44	1
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922 NJPB [†] , oak	0.56 ^d	0.42	1
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923	NJPB [†] , Ericaceous	0.78 ^d	0.54	1
924	LUQ [†] , lower plot	0.8 ^e	0.55	1
925	LUQ [†] , upper plot	0.9 ^e	0.59	1
926	LUQ [†] , control forest	0.4 ^e	0.32	1
927				
928		<i>Simulation</i>		
929		1.95 ^f	0.85 ^f	— ^g
930				

931 [†]Abbreviations of names of places (locations): LUQ: Luquillo Experimental Forest,
932 Puerto Rico (18°N, 5°W); GSF: Guanica State Forest, Puerto Rico (17°N, 65°W); RKF:
933 Ryukoku Forest, Japan (34°N, 135°E); WBNP: Wood Buffalo National Park, Canada
934 (68°N, 113°W); NJPB: New Jersey Pine Barrens, USA (39°N, 74°W).

935 [‡]Calculation was based on field data from experiments each consisting of several periods
936 that lasted 30—92 days during non-winter seasons.

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939 **Figure captions**

940 Fig. 1 A compartment model representing the mass balance of organic matter that is
941 derived from live fine roots in the soil volume. The boxes express the stock: B is live
942 fine roots and N is dead fine roots and organic matter of fine root origin. The arrows
943 indicate mass flow into, between, or out of the compartments: g_{ij} is fine root ingrowth; m_{ij}
944 is fine root mortality; and d_{ij} is decomposition of dead organic matter between the times i
945 and j . The amounts of live fine roots at times i and j are expressed as B_i and B_j ,
946 respectively, in the text. N_i and N_j express the amounts of necromass at times i and j ,
947 respectively. ΔB and ΔN represent changes in fine root biomass and necromass
948 between times i and j .

949

950 Fig. 2 A sequence of soil core installations into the soil horizon (open circles) and
951 recovery or soil core sampling to measure fine root biomass and necromass (filled circles)
952 of a set of three soil cylinders used to evaluate fine root ingrowth, mortality, and
953 decomposition simultaneously between times i and j , where $0 < i < j$. For ingrowth
954 cores, the cores A and B are installed at the same time (time zero) but are recovered at
955 different times. For sequential soil sampling, soil cores A and B are collected at times
956 i and j , respectively. Litter bag C is the ‘root-impermeable water-permeable (RIWP)

957 sheet'-covered core installed with known mass of dead fine roots added at time i, and
958 recovered at time j with core B.

959

960 Fig. 3 Estimated values of fine root decomposition (d_{ij}), mortality (m_{ij}), and
961 production (g_{ij}) for the ingrowth core experiment of 2007. The estimates are compared
962 to those calculated by the decision matrix (DM, cross pattern), forward estimate (F, left-
963 slanting pattern), continuous inflow estimate (C, black), and backward estimate (B, right-
964 slanting pattern). Vertical bars indicate the upper 95% confidence limits based on the
965 bootstrap method. For the decision matrix method, all decomposition estimates are zero
966 except for the fourth period that ended on December 21. Note that the vertical scale is
967 different for fine root production, g_{ij} .

968 ^aThe values of fine root production were set at zero due to the negative values obtained.

969 See text for further explanation.

970

971 Fig. 4 Estimated values of fine root decomposition (d_{ij}), mortality (m_{ij}), and
972 production (g_{ij}) for the sequential soil core sampling of 2010. The estimates are
973 compared to those calculated by the decision matrix (DM, cross pattern), forward
974 estimate (F, left-slanting pattern), continuous inflow estimate (C, black), and backward
975 estimate (B, right-slanting pattern). Vertical bars indicate the upper 95% confidence
976 limits based on the bootstrap method. For the decision matrix method, all
977 decomposition estimates are zero. Note that the vertical scale is different for fine root
978 decomposition, d_{ij} .

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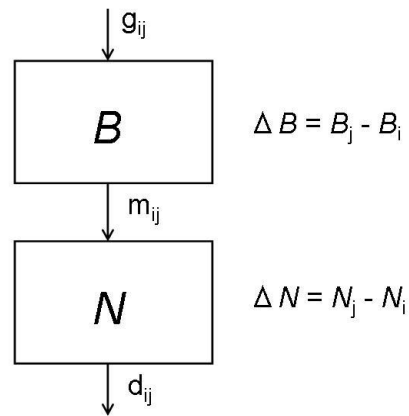
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986 **Figures**

987



988 **Fig. 1**

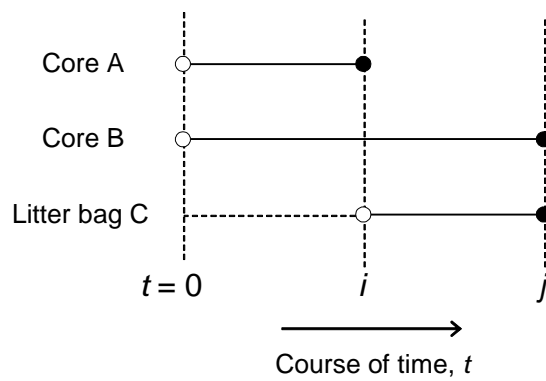
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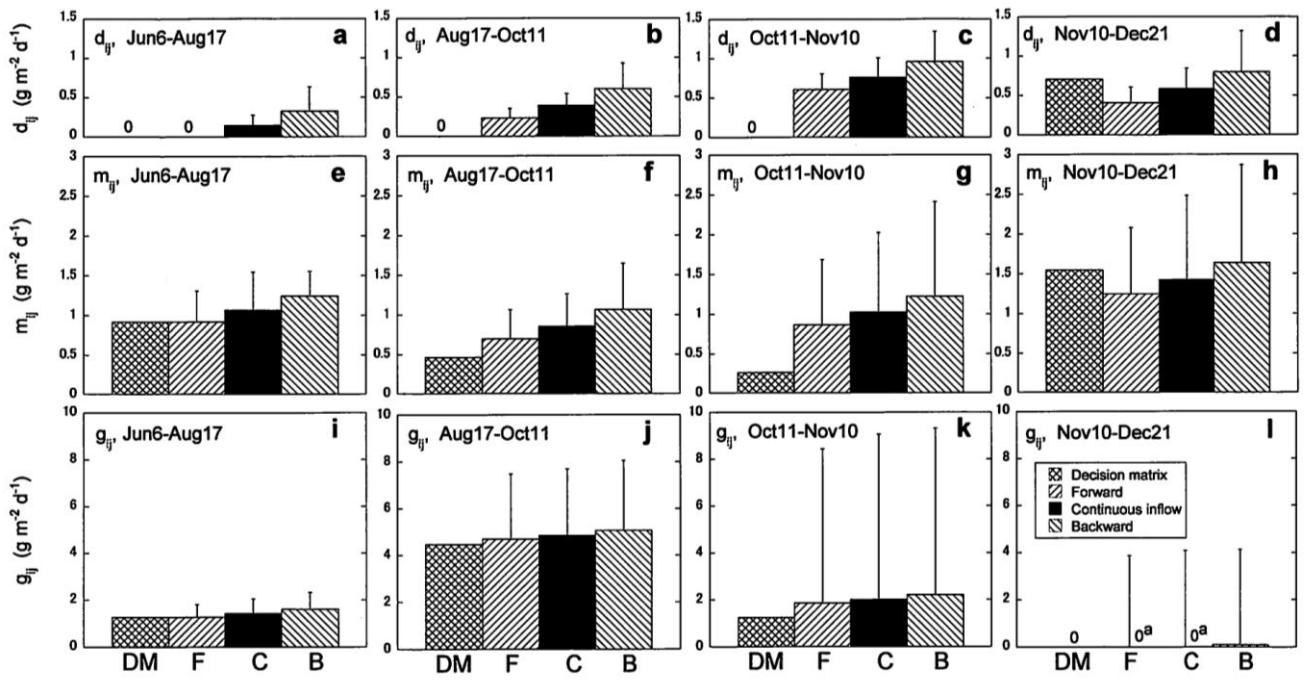


994 **Fig. 2**

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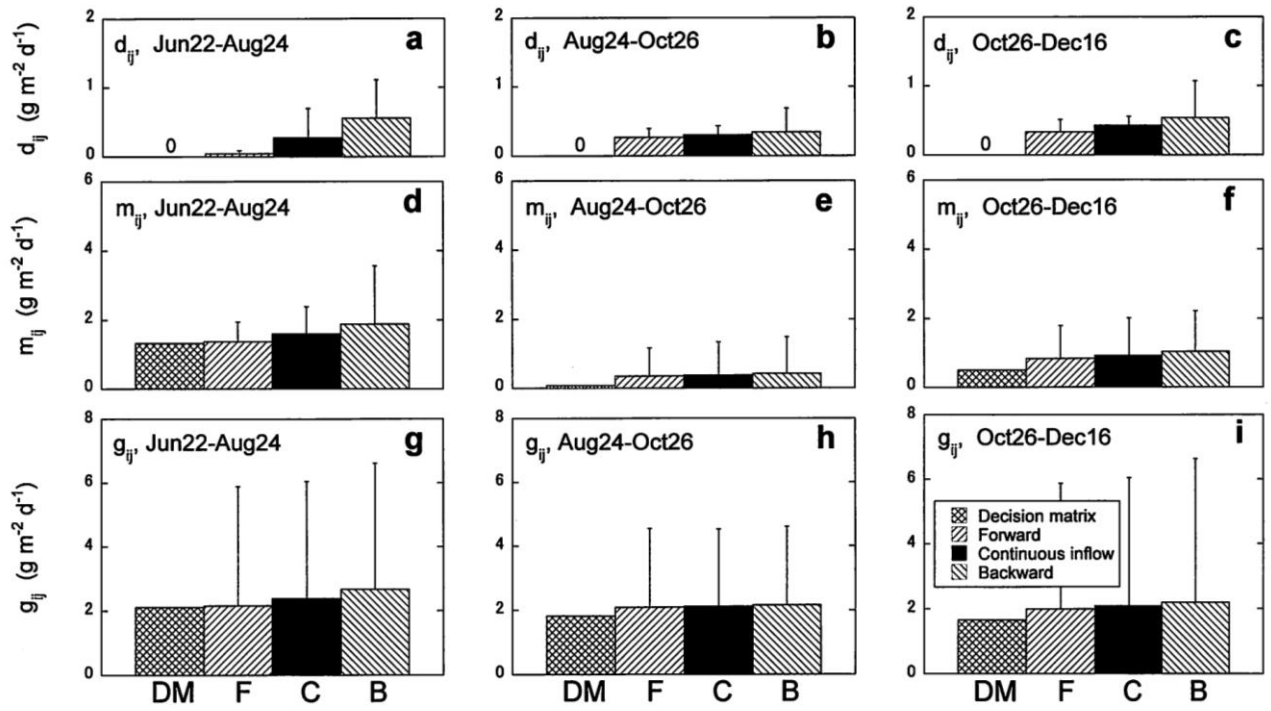
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999 **Fig. 3**

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1003 **Fig. 4**

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