

Additional supporting material for the research paper:

Forests may need centuries to recover their original productivity after continuous intensive management: an example from Douglas-fir stands

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1. FORECAST model description

The ecosystem management simulation model FORECAST (Kimmins and others 1999) has been used as a long-term management evaluation tool in several types of forest ecosystem (e.g., Morris and others 1997; Wei and others 2000, 2003; Seely and others 2002; Welham and others 2002), including tropical and sub-tropical plantations (Bi and others 2007; Blanco and González 2010). Evaluation exercises have demonstrated the reliability of this model (Blanco and others 2007; Seely and others 2008; Blanco and González 2010). FORECAST was specifically designed to examine the impacts of different management strategies or natural disturbance regimes on long-term site productivity. The projection of stand growth and ecosystem dynamics is based on a representation of the rates of key ecological processes regulating the availability of, and competition for, light and nutrient resources (Figure S1). The rates of these processes are calculated from a combination of historical bioassay data (biomass accumulation in component pools, stand density, etc.) and measures of certain ecosystem variables (e.g. decomposition rates, photosynthetic saturation curves) by relating ‘biologically active’ biomass components (foliage and small roots) to calculations of nutrient uptake, the capture of light energy, and net primary production. Using this ‘internal calibration’ or hybrid approach, the model generates a suite of growth properties for each tree and plant species to be represented. These growth properties are subsequently used to model growth as a function of resource availability and competition (Kimmins and others 1999). They include (but are not limited to): 1) Photosynthetic efficiency per unit foliage biomass based on relationships between foliage biomass, simulated self-shading, and net primary productivity after accounting for litterfall and mortality; 2) Nutrient uptake requirements based on rates of biomass accumulation and literature- or field-based measures of nutrient concentrations in different biomass components on different site qualities; 3) Light-related measures of tree and branch mortality derived from stand density input data in combination with simulated light profiles. Light levels at which foliage and tree mortality occur are estimated for each species.

Soil fertility in FORECAST is represented based on empirical input data describing decomposition (mass loss) rates and changes in chemistry as decomposition proceeds. These data allow for the calculation of nutrient release from litter and humus (Figure S1). Nutrient uptake demands of different species on sites of different fertility are based on observed biomass

accumulation rates and tissue nutrient concentrations on these sites, allowing for internal cycling of nutrients. The calculated uptake demand by the observed growth rates on sites of different productivity permits a definition of nutritional site quality. This assumes that moisture is not the major limiting factor, or that, if it is limiting, it acts dominantly through soil processes that determine nutrient availability. In the humid climates that characterise the Chinese fir region this assumption is felt to be reasonable.

Carbon allocation in response to soil fertility and tree/plant nutrition is based on empirical biomass ratios and biomass turnover rates (e.g., number of years of leaf retention for evergreens) for sites of different fertility (e.g., different site nutritional quality), and on literature or locally-obtained values for variation in fine root turnover along fertility gradients. FORECAST performs many of its calculations at the stand level but includes a submodel that disaggregates stand-level productivity into the growth of individual stems with user-inputted information on stem size distributions at different stand ages. Top height and diameter at breast height (DBH) are calculated for each stem and used in a taper function to calculate total and individual gross and merchantable volumes.

2. Model sensitivity analysis

Kimmins et al. (1999) identified a list of parameters for which the model was the most sensitive. Among them, two parameters stand out due to the practical difficulty of obtaining data to estimate them: wood decomposition rate and fine root mortality (Kimmins et al. 2004). To study the sensitivity of the model to uncertainty in the calibration of those parameters, the calibration values were modified in +20%, +10%, -10%, -20% and the relative difference in two target variables: total tree biomass and soil organic matter. Sensitivity analysis showed that relative changes in tree biomass and SOM were always smaller than changes in the calibration parameters. The modification in a tree physiological parameter (fine root turnover) affected more tree biomass than SOM, whereas changes in a soil parameter (wood decomposition rate) affected more SOM than tree biomass (Table 3). The recovery patterns were not significantly changed by the sensitivity analysis at any site (see Supplementary material). These results indicate that the model was only moderately sensitive to two of the main tree and soil parameters, showing its capability to reduce error propagation through the simulation (Kimmins et al. 2010).

3. Supplementary references

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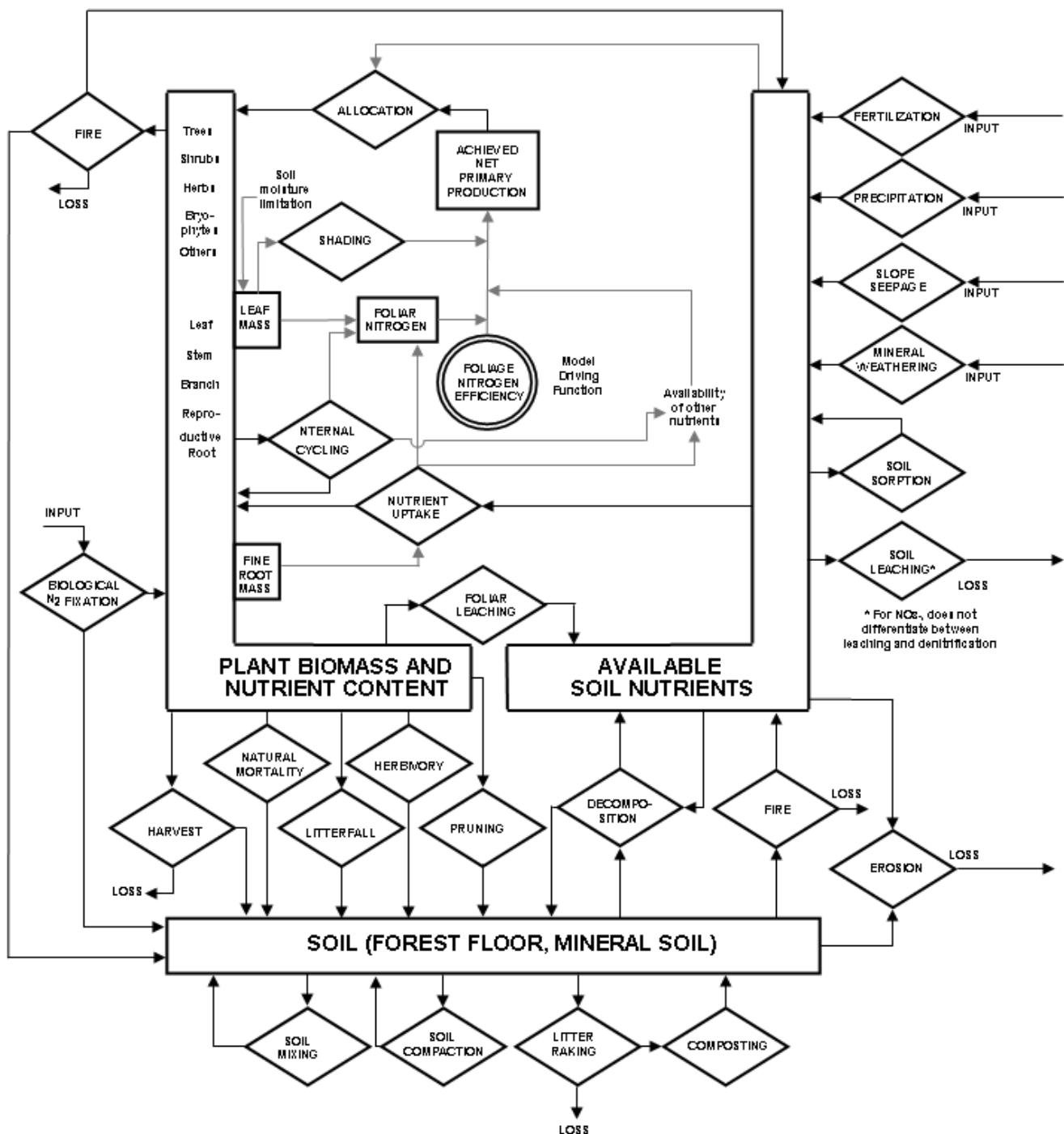


Figure S1. A schematic representation of the ecosystem compartments and transfer pathways represented in FORECAST (adapted from Kimmins et al. 1999).

Table S1. Values used to calibrate FORECAST parameters related to Douglas-fir. Nitrogen concentration data were obtained from (Taylor et al. 1992). Allometric equations: Y_n : biomass of each biomass fraction per tree in kg; D: diameter at breast height in cm; H: height in m. Decomposition rates indicate the mass loss in one year as a fraction of the initial mass at that year.

Parameter ^a	Unit	Rich site	Poor site	Allometric equation ^b
Nitrogen concentration in needles young / old / dead	%	1.09 / 1.00 / 0.49	0.98 / 0.91 / 0.44	Y_1 (needles) = 10.3 + 3.9 · D ² · H
Nitrogen concentration in stem sapwood / heartwood	%	0.11 / 0.06	0.08 / 0.05	Y_2 (stemwood) = 10.3 + 110.4 · D ² · H
Nitrogen concentration in bark live / dead	%	0.30 / 0.27	0.28 / 0.26	Y_3 (bark) = 3.1 + 15.6 · D ² · H
Nitrogen concentration in branches live / dead	%	0.37 / 0.22	0.33 / 0.19	Y_4 (branches) = 1.4 + 6.0 · D ² · H
Nitrogen concentration in root sapwood / heartwood	%	0.11 / 0.05	0.08 / 0.04	Y_5 (roots) = 0.16 · (Y ₁ + Y ₂ + Y ₃ + Y ₄)
Nitrogen concentration in fine roots live / dead	%	0.72 / 0.42	0.68 / 0.32	Y_6 good = 0.289 · Y ₁ ; Y_6 poor = 0.397 · Y ₁
Shading by maximum foliage biomass	% of full light	15	20	-
Soil volume occupied at maximum fine root biomass ^c	%	80	85	-
Efficiency of N root capture	%	98	98	-
Retention time for young / old foliage / dead branches	years	2 / 3 / 40	2 / 4 / 25	-
Fine roots turnover ^c	year ⁻¹	0.80	1.03	-
Decomposition rates ^d				Litter age in years (decomposition rate in %)
Sapwood (by litter age)	% year ⁻¹	1-10 years (1.1); 11-25 years (3.2); 26-40 years (8.0); >40 years (2.5)		
Heartwood	% year ⁻¹	1-10 years (0.9); 11-25 years (3.0); 26-45 years (6.0); >45 years (2.5)		
Bark	% year ⁻¹	1-10 years (14.0); 11-16 years (12.0); >16 years (2.5)		
Branches and large roots	% year ⁻¹	1-10 years (10); 11-18 years (12.0); >18 years (3.0)		
Needles (poor site)	% year ⁻¹	1-2 years (25.0); 3-10 years (23.0); >10 years (4.0)		
Needles (good site)	% year ⁻¹	1-2 years (27.0); 3-10 years (21.0); >10 years (3.0)		
Fine roots	% year ⁻¹	1-3 years (14.0); 4-6 years (12.0); 7-15 years (10.0); >15 years (8.0)		

a. Nitrogen concentration data from (Mitchell et al. 1996, Trofymow et al. 1991, Hawkins and Henry 1999).

b. Data from (Standish et al. 1985).

c. Data from (Kurz and Kimmings 1987).

d. Data from (Prescott et al. 2000, Taylor et al. 1991).

Table S2. Values used to calibrate FORECAST parameters related to Salal and soil processes. Decomposition rates indicate the mass loss in one year as a fraction of the initial mass at that year.

Salal parameters ^a	Unit	Rich site	Poor site
Nitrogen concentration in leaves live / dead	%	1.20 / 0.70	0.90 / 0.65
Nitrogen concentration in stems live / dead	%	0.25 / 0.14	0.20 / 0.12
Nitrogen concentration in rhizomes live / dead	%	0.30 / 0.17	0.25 / 0.15
Nitrogen concentration in roots live / dead	%	0.75 / 0.45	0.70 / 0.40
Shading by maximum foliage biomass	% of full light	0.28	0.34
Soil volume occupied at maximum fine root biomass	%	55	65
Efficiency of N root capture	%	99	99
Transfer from live to dead stem / rhizomes / roots	% year ⁻¹	10 / 10 / 65	10 / 10 / 70
Retention time for foliage	years	3	3
Decomposition rates ^b		Litter age in years (decomposition rate in %)	
Foliage (poor site)	% year ⁻¹	1-3 years (40.0); 4-6 years (20.0); 7-10 years (10.0); >10 years (3.0)	
Foliage (rich site)	% year ⁻¹	1-3 years (45.0); 4-6 years (18.0); 7-10 years (10.0); >10 years (3.0)	
Stems & roots	% year ⁻¹	1-2 years (30.0); 3-5 years (20.0); 6-15 years (10.0); >15 years (0.4)	
Soil parameters		Rich site	Poor site
Nitrogen concentration in slow / fast humus	%	2.75 / 1.20	2.75 / 1.20
Decomposition rate slow / fast humus	% year ⁻¹	0.17 / 3.00	0.17 / 3.00
CEC soil (CEC humus) / AEC ^c	kg N ha ⁻¹	90.0 (0.2) / 7.0	70.0 (0.2) / 5.0
Atmospheric deposition ^d / non-symbiotic fixation	kg N ha ⁻¹ year ⁻¹	2.5 / 1.0	2.5 / 1.0
Initial soil organic matter (humus + litter)	Mg ha ⁻¹	213.7	147.8
Non-symbiotic N fixation rate	Kg N ha ⁻¹	2.5	3.0

a. Nitrogen concentration data from Stanek et al. (1979) and Messier and Mitchel (1994).

b. Data from Prescott et al. (2000) and Taylor et al. (1991).

c. CEC: Cation exchange capacity of mineral soil (kg N ha⁻¹) and of humus (kg N ha⁻¹ CEC / Mg ha⁻¹ humus). AEC: Total soil anion exchange capacity.

d. Data from Chambers et al. (2001).

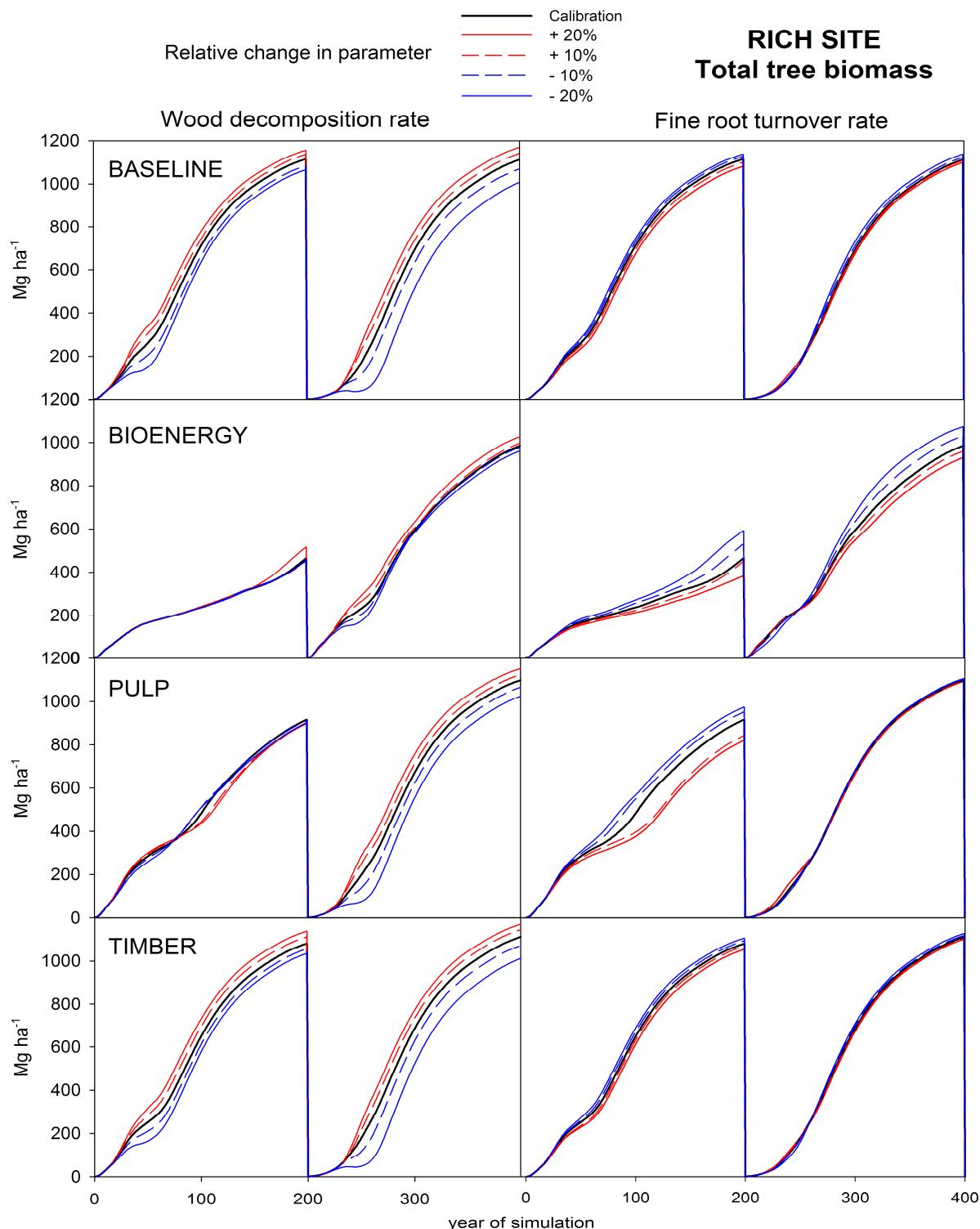


Figure S2. Sensitivity analysis of tree biomass predictions to changes in wood decomposing rate (left panels) and fine root turnover rate (right panels) in 4 different post-management scenarios in a rich site.

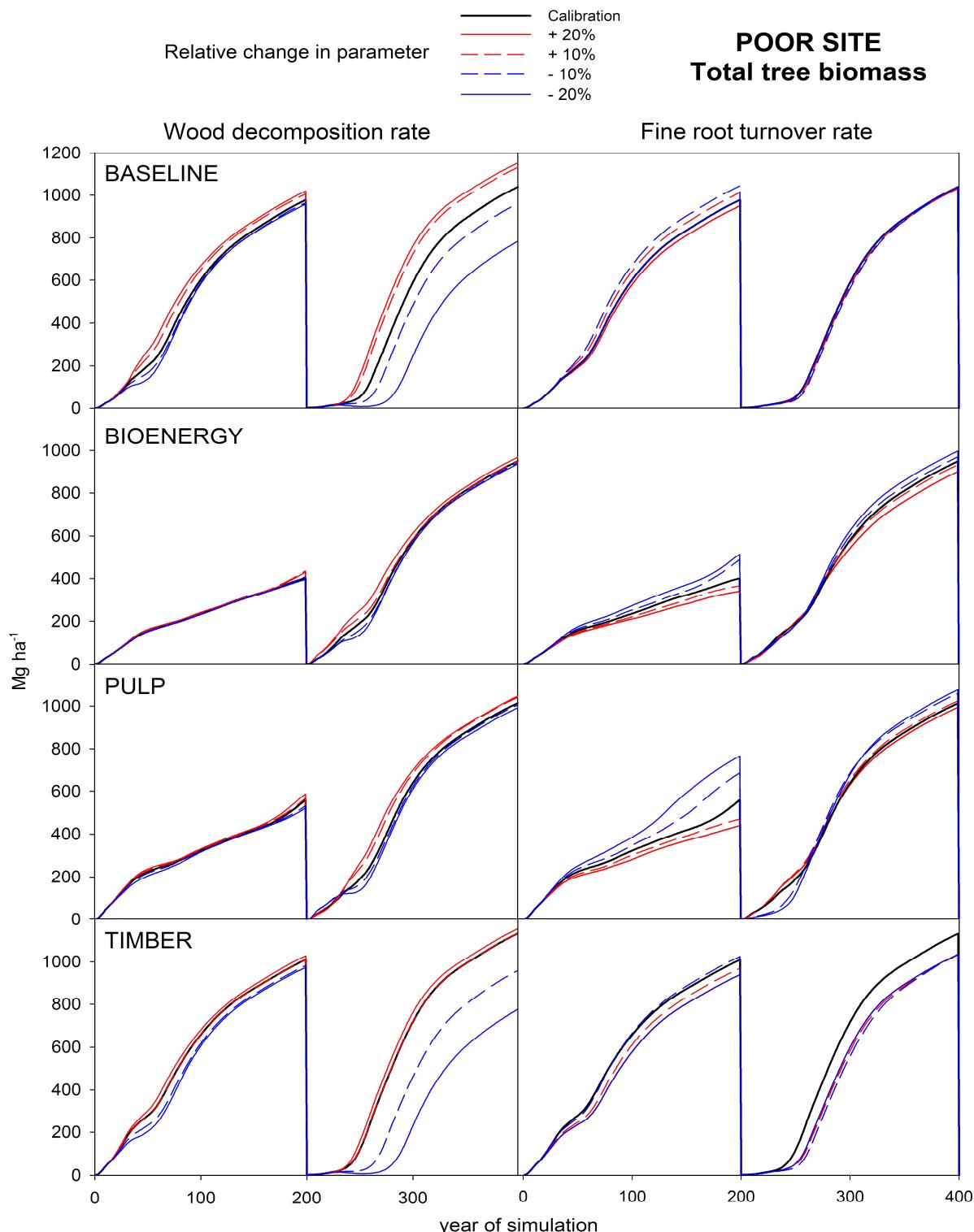


Figure S3. Sensitivity analysis of tree biomass predictions to changes in wood decomposing rate (left panels) and fine root turnover rate (right panels) in 4 different post-management scenarios in a poor site.

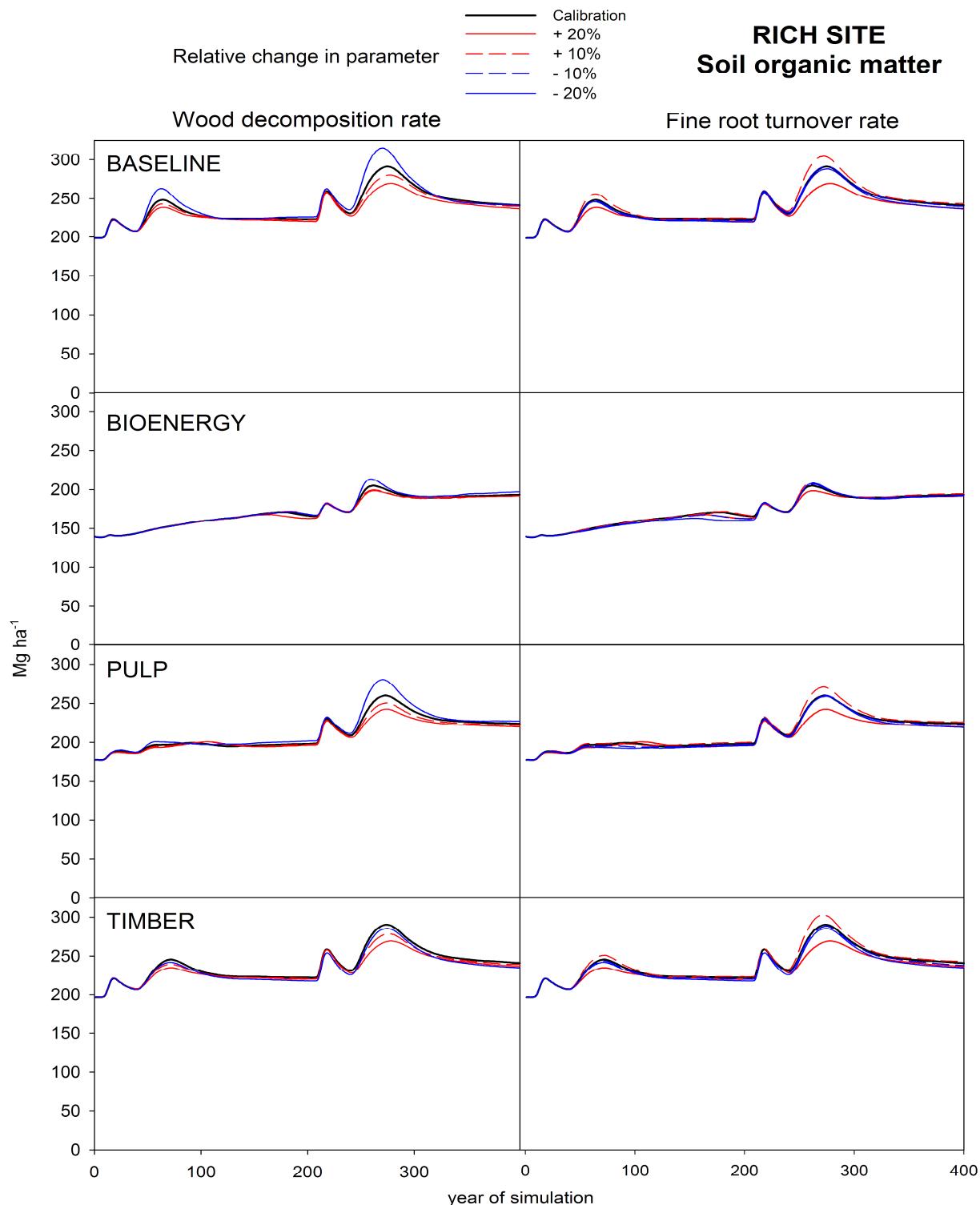


Figure S4. Sensitivity analysis of SOM predictions to changes in wood decomposing rate (left panels) and fine root turnover rate (right panels) in 4 different post-management scenarios in a rich site.

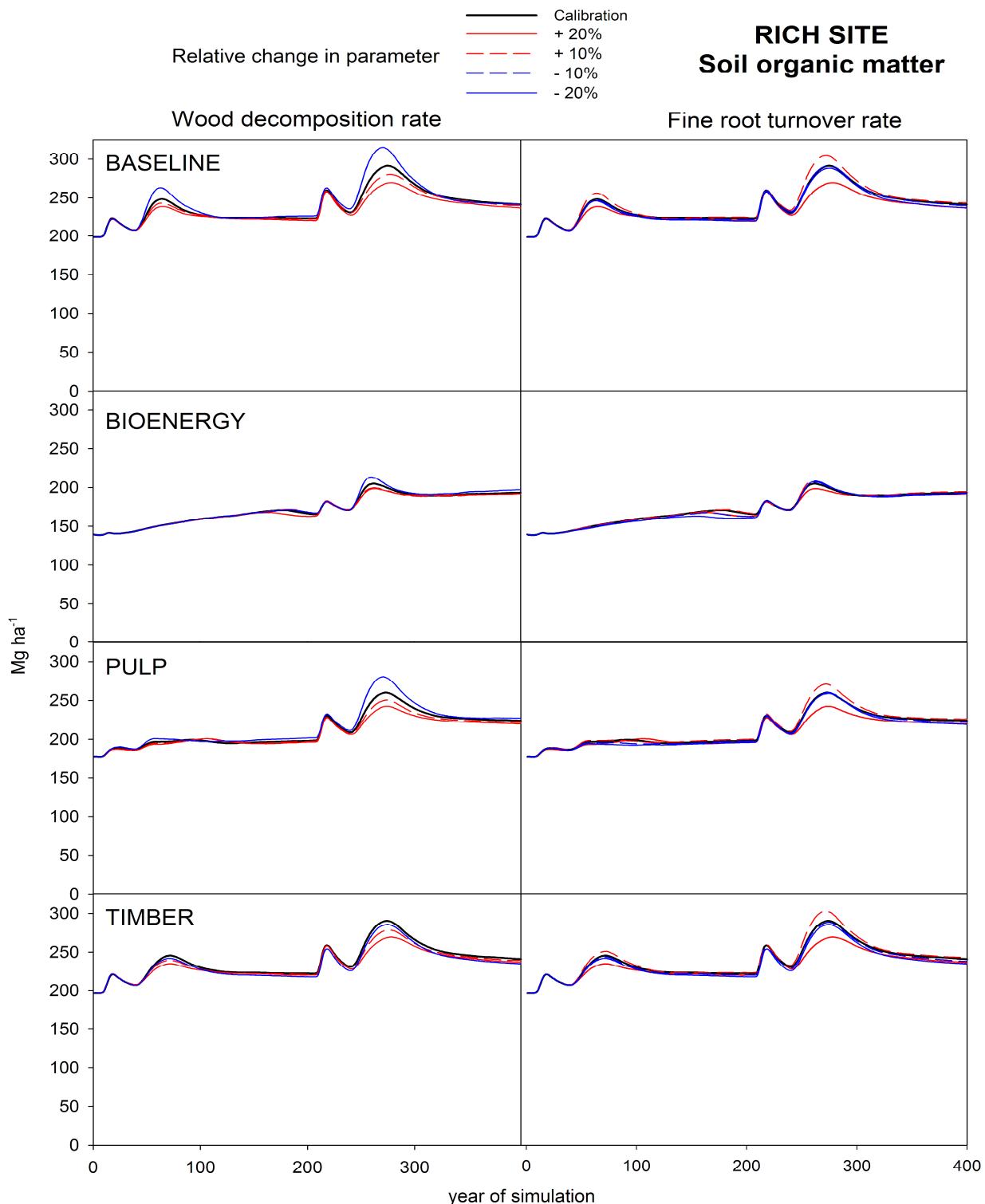


Figure S5. Sensitivity analysis of SOM predictions to changes in wood decomposing rate (left panels) and fine root turnover rate (right panels) in 4 different post-management scenarios in a rich site.