Effects of forest management on productivity and carbon sequestration: a review and hypothesis

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Abstract

With an increasing fraction of the world's forests being intensively managed for meeting humanity's need for wood, fiber and ecosystem services, quantitative understanding of the functional changes in these ecosystems in comparison with natural forests is needed. In particular, the role of managed forests as long-term carbon (C) sinks and for mitigating climate change require a detailed assessment of their carbon cycle on different temporal scales. In the current review we assess available data on the structure and function of the world's forests, explore the main differences in the C exchange between managed and unmanaged stands, and explore potential physiological mechanisms behind both observed and expected changes. Two global databases that include classification for management indicate that managed forests are about 50 years younger, include 25% more coniferous stands, and have about 50% lower C stocks than unmanaged forests. The gross primary productivity (GPP) and total net primary productivity (NPP) are the similar, but relatively more of the assimilated carbon is allocated to aboveground pools in managed than in unmanaged forests, whereas allocation to fine roots and rhizosymbionts is lower. This shift in allocation patterns is promoted by increasing plant size, and by increased nutrient availability. Long-term carbon sequestration potential in soils is assessed through the ratio of heterotrophic respiration to total detritus production, which indicates that (i) the forest soils may be losing more carbon on an annual basis than they regain in detritus inputs, and (ii) the deficit appears to be greater in managed forests. While climate change and management factors (esp. fertilization) both contribute to greater carbon accumulation potential in the soil, the harvest-related increase in decomposition affects the C budget over the entire harvest cycle. Although the findings do not preclude the use of forests for climate mitigation, maximizing merchantable productivity may have significant carbon costs for the soil pool. We conclude that optimal management strategies for maximizing multiple benefits from ecosystem services require better understanding of the dynamics of belowground allocation, carbohydrate availability, heterotrophic respiration, and carbon stabilization in the soil.

Productivity and C sequestration

Plantation forests, including loblolly pine, are among the most productive ecosystems on Earth, largely due to the management practices that relieve growth limitations. Further aided by global rise in CO_2 and N deposition, managed forests play a significant role in the increase of forest NPP over the past century. However, high merchantable productivity does not necessarily translate to high long-term carbon sequestration in the soil. Detecting a direct change in soil C pool is difficult due to its large size, spatial variability and measurement uncertainties. The ratio of input and output fluxes offers an alternative to pool measurements, and was applied here using two global databases with nearly 4000 site-years.

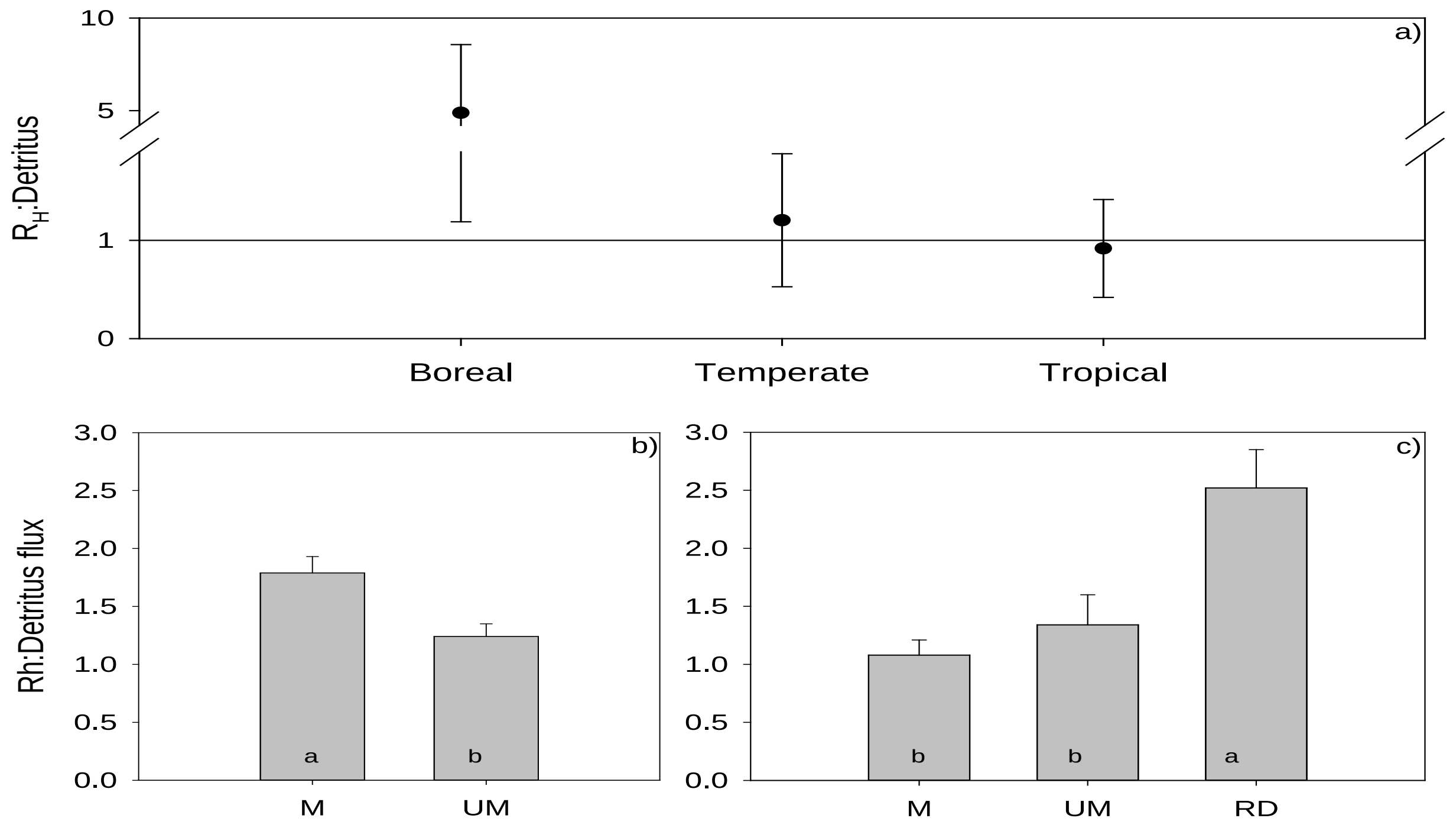

Figure 2. The ratio of heterotrophic respiration (Rh) to total detritus production (Detritus flux) as an estimate of soil carbon balance on an annual basis. (a) the global means of forests by biome, (b, c) means by management type – managed (M), unmanaged (UM) or recently disturbed (RD) – in the temperate biome (the only biome where data from managed forests was available). Panels (a) and (b) are based on SRDB database (Bond-Lamberty and Thomson, 2010a), and panel (c) is based on the NPP database (Luyssaert et al., 2009).

Full study:

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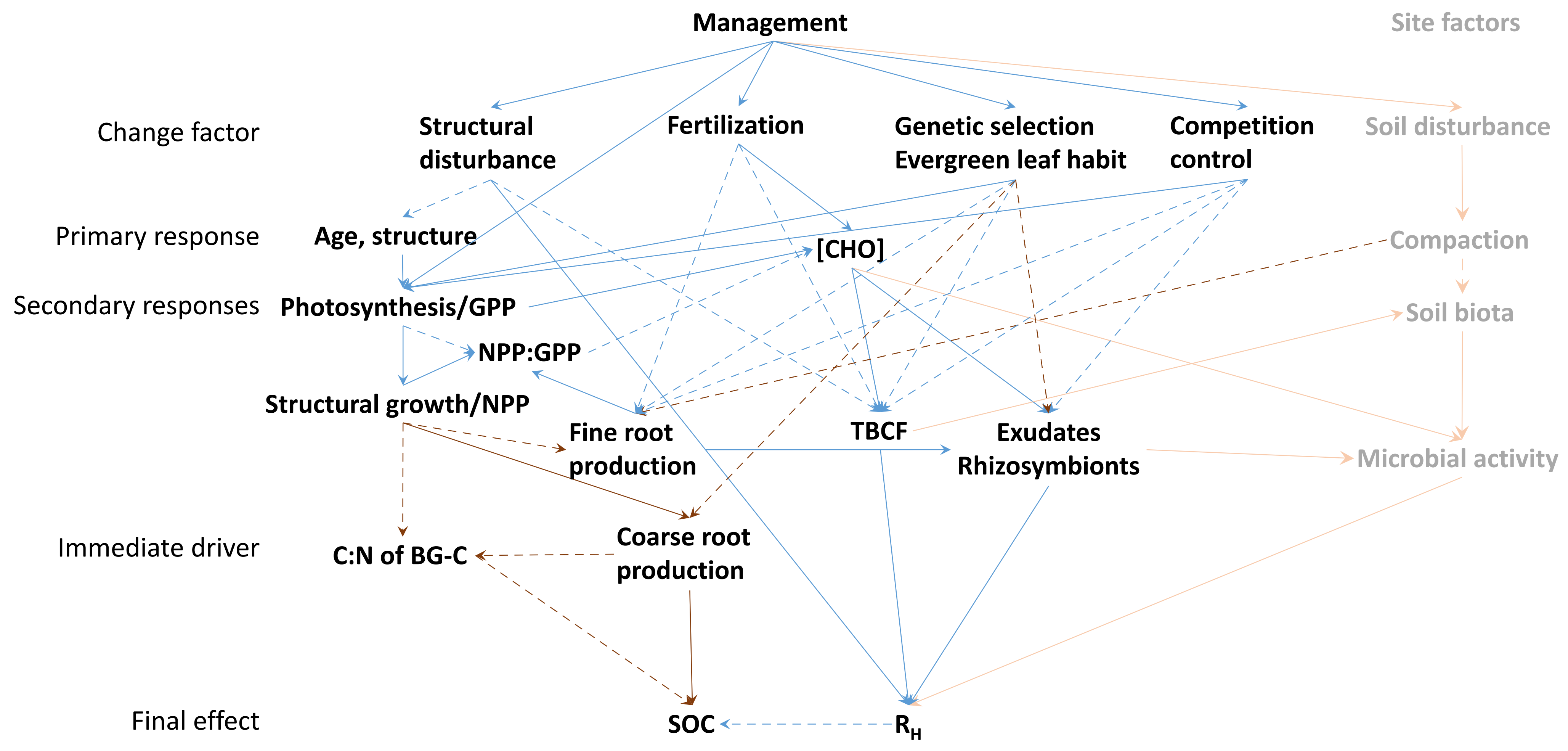

Management
Site factors
Change factor
Structural disturbance
Fertilization
Genetic selection
Evergreen leaf habit
Competition control
Soil disturbance
Primary response
Age, structure
[CHO]
Compaction
Secondary responses
Photosynthesis/GPP
Soil biota
NPP:GPP
Structural growth/NPP
Fine root production
TBCF
Exudates
Rhizosymbionts
Microbial activity
Immediate driver
C:N of BG-C
Coarse root production
Final effect
SOC
R_H

Figure 1. Flow chart of management effects on forest productivity and carbon sequestration. Solid arrows indicate positive effect, and dashed arrows negative. Brown arrows mark processes affecting the recalcitrance of soil carbon. Orange arrows mark processes operating through soil disturbance that in the current study are discussed only superficially. Abbreviations: GPP – gross primary productivity, NPP – net primary productivity, [CHO] – carbohydrate concentration, TBCF – total belowground carbon flux, C:N – the ratio of carbon to nitrogen, BG-C – belowground carbon, SOC – soil organic carbon, R_H – heterotrophic respiration.

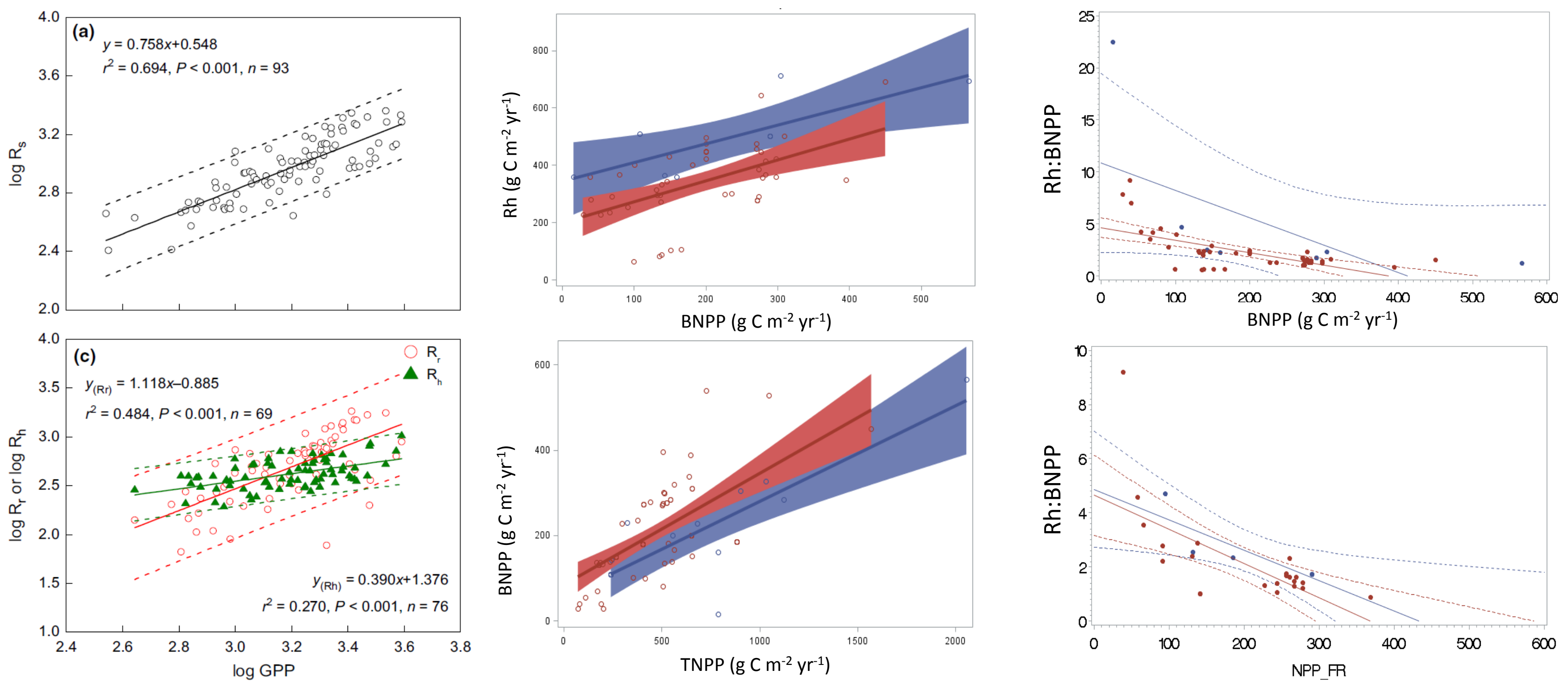

Figure 3. Correlation between total soil respiration (Rs), heterotrophic respiration (Rh) and the ratio of Rh to belowground net primary production with different metrics of production. Leftmost panels from Chen et al. 2014.

Summary

1. Functional differences between managed and natural forests are rooted largely in their different structure.
   1. Managed forests are on average 50 years younger than natural ones, have about 50% less biomass and soil C, and 25% lower LAI.
   2. While gross photosynthesis does not differ by management status, the respiration costs do, and net ecosystem productivity is about 50% greater in managed than natural forests.
   3. Heterotrophic respiration (Rh) increased with total as well as belowground productivity, whereas the ratio of Rh:BNPP decreased.
   4. In net balance, soils of both managed and natural unmanaged forests appear to be losing more carbon than they received in annual detritus production. The imbalance is greater in managed forests, and is attributable to the intensity of management activities.
2. The potential of forest management to contribute to long-term carbon sequestration seems in doubt. Although the finding of wide-spread soil C deficit is controversial and contrary to current main-stream thinking of the role of forest soils in the global C cycle, there is a growing body of evidence suggesting that soil C is more vulnerable to decomposition than thought even a decade ago. Several harvesting-related changes including physical disturbance, priming by fresh C inputs associated with root regrowth, and increased C:N ratio associated with harvest residue input are known to stimulate Rh and soil C loss.
3. On the other hand, climate change (temperature, CO_2) and some management factors (fertilization, species selection) are expected to increase C allocation to woody tissues, including coarse roots, which could contribute to greater soil C pool. Furthermore, the allometric decrease in proportional belowground allocation appears to be offset by isometric absolute increase in total belowground flux due to greater overall productivity in managed forests. Thus, the potential to sequester carbon in long-lived soil pool rests on the balance between disturbances-driven Rh and allocation- and management-driven belowground inputs. In particular, managing of harvest residue may offer climate mitigation benefits.

Table 1. Global mean (±SE) carbon pools, fluxes and their ratios in managed and unmanaged forests. The significance of the differences is indicated with the superscript letters, and is considered significant at p<0.05 level. The analyses were based on the NPP (Luyssaert et al., 2009) and SRDB (Bond-Lamberty and Thomson, 2010a) databases.

Database	NPP		SRDB	
Metric (C pool, flux or flux ratio)	**Managed**	**Unmanaged**	**Managed**	**Unmanaged**
Aboveground biomass carbon (g m^{-2})	n/a	n/a	3465 ± 1104 ^{b}	8870 ± 1042 ^{a}
Belowground biomass carbon (g m^{-2})	n/a	n/a	821 ± 249 ^{b}	1463 ± 178 ^{a}
Coarse root carbon (g m^{-2})	n/a	n/a	515 ± 191 ^{a}	599 ± 189 ^{a}
Fine root carbon (g m^{-2})	n/a	n/a	235 ± 197 ^{b}	439 ± 176 ^{a}
Litter carbon (g m^{-2})	n/a	n/a	1164 ± 366 ^{a}	1764 ± 258 ^{a}
Mineral soil carbon (g m^{-2})	n/a	n/a	6246 ± 1749 ^{b}	11356 ± 1305 ^{a}
LAI (m^2 m^{-2})	n/a	n/a	3.4 ± 0.3 ^{b}	4.5 ± 0.2 ^{a}
Mean tree age (yr)	n/a	n/a	21 ± 3 ^{b}	68 ± 3 ^{a}
GPP (g C m^{-2} yr^{-1})	1817 ± 32^a	1806 ± 41 ^{a}	1989 ± 169 ^{a}	1887 ± 159 ^{a}
TNPP (g C m^{-2} yr^{-1})	668 ± 65 ^{a}	675 ± 68 ^{a}	674 ± 75 ^{a}	595 ± 32 ^{a}
NPPstem (g C m^{-2} yr^{-1})	196 ± 33 ^{a}	170 ± 35 ^{a}	n/a	n/a
NPPfr (g C m^{-2} yr^{-1})	n/a	n/a	181 ± 18 ^{b}	225 ± 13 ^{a}
ANPP (g C m^{-2} yr^{-1})	365 ± 51 ^{a}	357 ± 54 ^{a}	651 ± 51 ^{a}	373 ± 41 ^{b}
BNPP (g C m^{-2} yr^{-1})	n/a	n/a	171 ± 21 ^{a}	173 ± 17 ^{a}
NEP (g C m^{-2} yr^{-1})	261 ± 16 ^{a}	176 ± 22 ^{b}	444 ± 84 ^{a}	300 ± 84 ^{b}
Litter production (g C m^{-2} yr^{-1})	n/a	n/a	210 ± 11 ^{a}	221 ± 9.6 ^{a}
Root litter production (g C m^{-2} yr^{-1})	n/a	n/a	178 ± 35 ^{a}	225 ± 28 ^{a}
Total detritus production (g C m^{-2} yr^{-1})	n/a	n/a	377 ± 43 ^{b}	491 ± 35 ^{a}
Re (g C m^{-2} yr^{-1})	1562 ± 27 ^{a}	1617 ± 35 ^{a}	1698 ± 94 ^{a}	1384 ± 80 ^{b}
Ra_{total} (g C m^{-2} yr^{-1})	1133 ± 102 ^{b}	1460 ± 112 ^{a}	n/a	n/a
Ra_{soil} (g C m^{-2} yr^{-1})	n/a	n/a	457 ± 66 ^{a}	377 ± 66 ^{b}
Rh_{total} (g C m^{-2} yr^{-1})	471 ± 29 ^{b}	558 ± 34 ^{a}	n/a	n/a
Rh_{soil} (g C m^{-2} yr^{-1})	n/a	n/a	499 ± 40 ^{a}	458 ± 40 ^{a}
Rs (g C m^{-2} yr^{-1})	923 ± 46 ^{a}	1013 ± 61 ^{a}	1006 ± 39 ^{a}	834 ± 33 ^{b}
Rlitter (g C m^{-2} yr^{-1})	n/a	n/a	220 ± 33 ^{b}	308 ± 32 ^{a}
TBCF (g C m^{-2} yr^{-1})	n/a	n/a	531 ± 111 ^{a}	561 ± 97 ^{a}
BGA (BNPP:TNPP)	0.37 ± 0.04 ^{a}	0.33 ± 0.04 ^{a}	n/a	n/a
Rh:Litter_flux (unitless)	4.3 ± 2.4 ^{a}	2.2 ± 2.4 ^{a}	n/a	n/a
Rlitter:Litter_flux (unitless)	n/a	n/a	0.83±0.11 ^{b}	1.20±0.07 ^{a}
Rh:Detritus1 (unitless); D=[leaves, fine roots]	1.4 ± 0.5 ^{a}	1.5 ± 0.6 ^{a}	3.4 ± 2.0 ^{a}	2.8 ± 1.6 ^{a}
Rh:Detritus2 (unitless); D=[leaves, all roots]	1.0 ± 0.4 ^{a}	1.0 ± 0.5 ^{a}	n/a	n/a
Rh:Total detritus flux (unitless) ^{1}	n/a	n/a	4.4 ± 2.3 ^{a}	3.8 ± 1.4 ^{a}
Soil C balance = Detritus1-Rh (g C m^{-2} yr^{-1})	-221 ± 42 ^{a}	-311 ± 44 ^{b}	n/a	n/a
Soil C balance = Detritus2-Rh (g C m^{-2} yr^{-1})	20 ± 43 ^{a}	-55 ± 53 ^{b}	n/a	n/a
SOC bal. = Total detritus flux-Rh (g C m^{-2} yr^{-1})	n/a	n/a	-214 ± 48 ^{b}	-114 ± 30 ^{a}

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