EFFECT OF HARVEST INTENSITY ON SOIL CARBON AND NUTRIENTS ACROSS GLOBAL FORESTS: A META-ANALYSIS

By

He Tian

Supervisor Han Y. H. Chen

Faculty of Natural Resources Management

Lakehead University

Thunder Bay, Ontario

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Abstract

Logging residues can retain important nutrients for tree growth after biomass harvesting. However, increasing the harvest intensity may decrease soil nutrient stores stocks and affect biomass productivity. Using 2207 observations from 51 published studies and 2207 observations in boreal, temperate and tropical forests, we assessed how soil carbon (C) and macronutrients (N, P, K, Ca, Mg) of regenerating stands respond to increasing harvest intensity from double slash (DS) to stem-only harvesting (SOH) to whole-tree harvesting (WTH).

Our meta-analysis reveals that forest harvesting has diverse effects on soil C, N and P, depending on elements, stocks vs. concentrations, soil layer, and harvesting intensity. We found that compared with SOH, WTH reduced carbon C and nitrogen N stocks in the forest floor, but not in the mineral soil, and had similarly negative effects on the concentrations of phosphorus P in the forest floor and mineral soil; DS had stronger positive effects on Magnesium concentrations in mineral soil compares to SOH.

Keywords: boreal forest; harvest intensity; harvest residue management; soil carbon stock; soil nitrogen stock; soil type; subtropical forest; temperate; tropical forest.

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INTRODUCTION

Due to the low commercial value, logging residues such as coarse and fine woody debris, unusable tops and branches, and cull trees are usually left on site after logging operations. (Farve and Napper, 2009). These residues decompose and release nutrients into the soil or the atmosphere, serving an integral role in nutrient cycling (Fontaine et al. , 2003). Organic matter (OM) derived from woody resides can directly affect a site's soil productivity by becoming a primary source of nutrients for vegetation growth. In addition, OM can improve soil productivity by supporting C cycling and sequestration, N availability, gas exchange, water availability, and biological diversity (Jurgensen et al., 1997). Finally, OM increases aeration, cation exchange capacity, soil aggregation, buffers soil pH changes and provides food and habitat for soil meso- and microfauna (Shepherd et al., 2002).

In the last 20 years, there has been a great number of research studies on the impact of residue management on soil C and nutrients in forests. Many studies found increasing biomass removal can reduce soil carbon (C) stocks and concentrations, with C reduction more pronounced in the forest floor than mineral soil layer (Nave et al. 2010; Achat et al. 2015b; Clarke et al. 2015). A synthesis report by Thiffault et al. (2011), using a vote-counting method to contrast WTH with SOH, shows that fewer studies reported negative effects than no effects on soil C and nitrogen (N) stocks and concentrations and N cycling in both forest floor and mineral soil. Also, most studies found increased N leaching and reduced soil phosphorus (P) and exchangeable cations from increasing biomass removal than no effects. These syntheses confirm that biomass harvesting may have negative effects on forest soils. However, divergent evidence from previous analyses indicates that the impacts of biomass harvesting on soil C and nutrients may also be dependent on harvest intensity, stand condition, climate zone, time since harvesting, nature of nutrient cycling, soil layer, *etc*.

To assess how soil carbon (C) and macronutrients (N, P, potassium (K) calcium (Ca), and magnesium (Mg)) of regenerating stands respond to increasing harvest intensity, we therefore grouped harvesting treatments into three categories: Stem-only harvesting (SOH), including both cut-to-length and tree-length harvesting; Whole-tree harvesting (WTH), SOH plus collection of primary residues generated from harvesting including tree tops, branches and/or leaves; Double slash harvesting (DS), Whole-tree harvesting plus double the amount of logging residues left on the site. This review collects relevant studies from boreal, temperate and tropical forests to presents a meta-analysis of their published experimental data. In this meta-analysis, we assess the impact of WTH and DS on soil C and nutrient stocks and concentrations in both forest floor and mineral soil.

METHODS

Data Collection

We searched Web of Science database for relevant peer-reviewed publications reporting on the impacts of biomass harvesting on forest ecosystems, specifically impacts on soil nutrients. Since the aim of the study is to assess the impact of biomass harvesting compared to stem-only harvesting, we selected studies that contrasted stem-only harvest against whole-tree harvesting (WTH) and double slash harvesting (DS).

For each study selected for analysis, we extracted data of the stocks and concentrations of soil C and macronutrients including N, P, K, Ca, and Mg in both forest floor and mineral soil layers. Results were reported graphically, using WebPlotDigitizer (http://arohatgi.info/WebPlotDigitizer/) to digitally extract data from figures. From original studies, we also obtained geographical locations, forest type (conifer, deciduous and mixed-wood), and soil type, biome (boreal, temperate, tropical, and subtropical) and time since harvesting (years). When a study reported a range value for time since harvesting, the midpoint of each ranged was used to represent the interval. Metadata collected by Thiffault *et al.* (2011) were kindly made available by the authors and were included in our dataset.

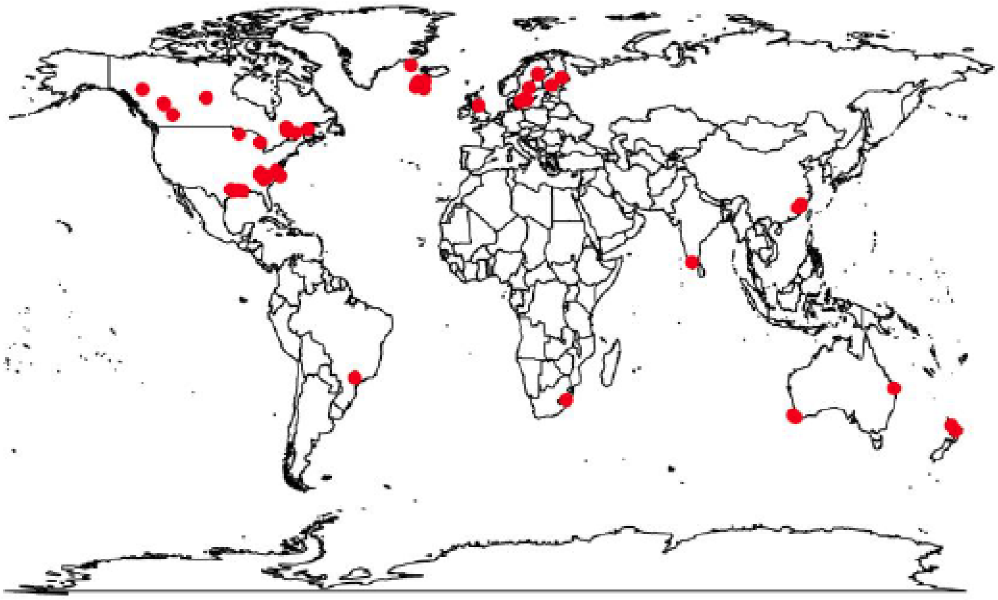

Figure 1: The global distribution of study sites included in the meta-analysis

Classification of harvest intensity

Although all possible types of biomass harvesting are individually of interest, sufficient experimental evidence does not exist to accurately examine impacts along the full gradient of harvesting intensities. We therefore grouped harvesting treatments into three categories: Stem-only harvesting (SOH), including both cut-to-length and tree-length harvesting; Whole-tree harvesting (WTH), SOH plus collection of primary residues generated from harvesting including tree tops, branches and/or leaves; Double slash harvesting (DS), Whole-tree harvesting plus double the amount of logging residues left on the site.

Data analysis

To examine the impacts of WTH and DS on soil C, nutrients, productivity and species diversity of post-harvest regenerating stands, we computed the natural log-transformed response ratio (ln*RR*) as the "effect size", which improves its statistical behavior in meta-analyses (Hedges *et al.* 1999):

$$\ln RR = \ln\left(\overline{X}_t / \overline{X}_c\right) = \ln \overline{X}_t - \ln \overline{X}_c \qquad (1)$$

where $\overline{X_t}$ is the mean value observed for the variable of interest in WTH or DS and $\overline{X_c}$ is mean value observed for the variable of interest in SOH.

Effect size estimates and subsequent inferences in meta-analysis may depend on how individual observations are weighted (Mueller *et al.* 2012; Ma & Chen 2016). Following previous work (Mueller *et al.* 2012; Pittelkow *et al.* 2015; Ma & Chen 2016), we weighted studies by replications rather than by sampling variance, since the latter was not reported for a significant number of studies included in our database. Moreover, weightings based on sampling variances could assign extreme importance to a few individual observations, and consequently average ln*RR* would be largely determined a small number of studies (Pittelkow *et al.* 2015; Ma & Chen 2016). The weight of each observation *i* in our dataset was calculated as:

$$w_i = \frac{n_t \times n_c}{n_t + n_c} \qquad (2)$$

where n_t and n_c are the numbers of replications corresponding each mean value observed in WTH or DS ($\overline{X_t}$) and SOH ($\overline{X_c}$). We also weighted all observations equally ($w_i = 1$). The results from two alternative weighting methods were qualitatively similar. We focus on reporting the results based on the weighting by replications.

We examined how the variations in harvest intensity (WTH and DS) on soil C and nutrients in both the forest floor and mineral soil layers. Since our data set was not sufficiently large to test all treatment combination levels among our categorical explanatory variables, we only tested the effects of harvest intensity. From fitted models, we derived 95% confidence intervals (CIs). When the 95% CIs does not cover zero, ln*RR* is significantly ($\alpha = 0.05$) different from zero. All statistical analyses were conducted with R.

RESULTS

Impacts of harvest intensity on soil carbon and nutrient concentrations and stocks

The impacts of biomass harvesting were dependent on harvest intensity and soil layer. Compared with SOH, WTH reduced C and N stocks and concentration in the forest floor, but not in the mineral soil (Fig. 2). There were similarly negative or marginally negative effects of WTH on Ca stocks and Ca concentration in both forest floor and mineral soil layers. Potassium and Mg stocks and K concentration were only reduced by WHT in mineral soil, while the concentrations of P were only reduced by WHT in forest floor. Compared with SOH, DS demonstrated no negative effect to all soil nutrients in both forest floor and mineral soil layer. And it increased the Magnesium stock in mineral soil layer.

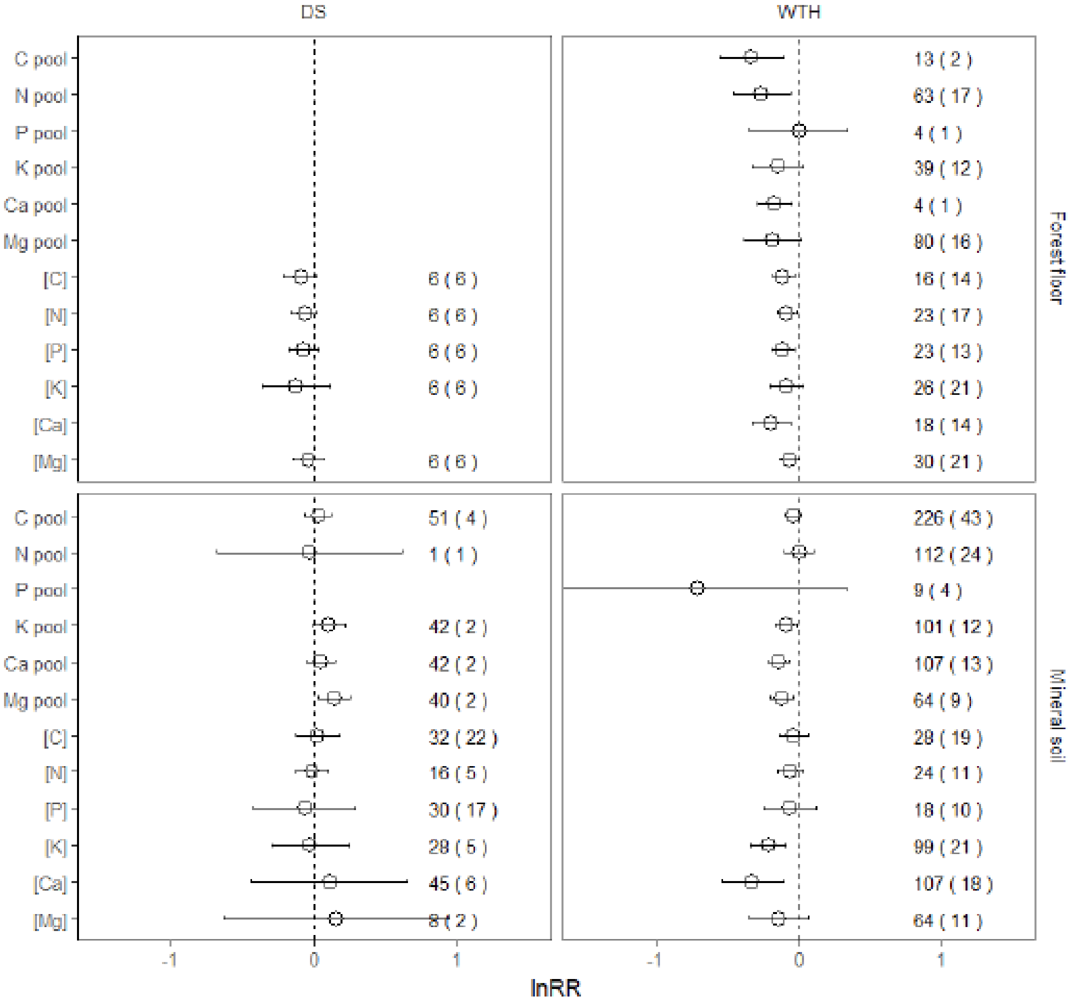

Figure 2: Effect size (lnRR) of harvesting on soil parameters as a function of harvest intensity by soil layer. Harvesting intensity included stem-only harvesting (SOH), whole-tree harvesting (WTH) and double slash harvesting (DS).

DISCUSSION

We found that whole tree harvesting had generally greater negative effects on soil C and macronutrients in the forest floor compares to mineral soil layer. The C, N and P concentrations were decreased in the forest floor and unaffected by harvesting in the mineral soil by WTH. The forest floor is more susceptible to be influenced by increasing harvest intensity. We also found high negative effects of increasing harvest intensity on soil Ca concentration and stocks in both forest floor and mineral soil. This finding suggests that using WTH instead of SO could increase the negative effects of biomass harvesting on soil C and macronutrients. Our results of the negative effects of WTH on soil C and nutrients are qualitatively similar with the results of previous analyses (Thiffault et al. 2011; Achat et al. 2015a). The increased reduction of forest floor C stocks with increasing harvest intensity is expected because additional removal of logging residues directly reduces the inputs of tree tops, branches and/or leaves into the forest floor (Nave et al. 2010). Increasing harvest intensity also reduced P concentration in forest floor, but not C, N and P concentration and stocks in in the mineral soil.

CONCLUSION AND FUTURE DIRECTIONS

Our analysis showed that 1) soil C and nutrients are generally reduced by biomass harvesting, and the extent of impacts on soil C and nutrient stocks and concentrations increases with amount of biomass removal, 2) the impacts of whole-tree harvesting on C and N stocks are stronger in the forest floor than in the mineral soil, but both forest floor and mineral soil experience similarly negative impacts in Ca cation stocks and concentrations; 3) DS had stronger positive effects on Magnesium concentrations in mineral soil compares to SOH.

Our results clearly demonstrate that soil C will be reduced by biomass harvesting. This result is no surprise. We note that increased forest biomass utilization could be a critical society decision to reduce the use of or reliance on fossil energy (Fargione et al. 2008), and could contribute to lessen rising atmospheric CO2 (IPCC 2013). Our findings of reduced soil nutrients (stocks and concentrations) associated with biomass harvesting concur with our expectations that more nutrient-rich tissues removed would yield less in-situ nutrients. However, we recommend (i) future efforts be focused on plant available nutrients; (ii) future studies shall consider comparing biomass harvesting versus wildfire on soil productivity since northern forests have evolved with adaptation to stand replacing disturbances, in particular wildfire, and soil nutrients recover rapidly following fire (Hume et al. 2016); (iii) our meta-data reflect findings from experimental sites. The number of observation is still limited and errors might exist during the process of data collection. It remains unsolved how experimentally conducted whole-tree harvesting compares with those done at forest operation. We concur with the previous speculations (Riffell et al. 2011) that the extent of biomass removal may be less in operational harvesting than experimental harvesting.

There is growing interest in the use of forest logging residues and non-merchantable biomass for bioenergy production. Greater utilization of residues can partially replace the use of fossil fuels, reducing longer-term greenhouse gas emissions and diversify a country's energy portfolio (Roach and Berch, 2014; Ter-Mikaelian et al., 2015). However, energy diversification and economic development should not compromise ecological sustainability (Lattimore et al., 2009), so we suggestion to use a low to medium harvest intensity like stem only harvest in the future logging residue management.

Appendix 1. List of studies included in the meta-analysis. (*1- Plant height, 2- [C], 3-[K], 4-[Ca], 5[Mg], 6-[N], 7-[P], 8-C, 9-N, 10- above ground biomass, 11-seedling survival, 12-basal area, 13-density of understory plants, 14-species richness, 15, species evenness, 16-Shannon's diversity, 17-Ca, 18-K, 19-P, 20-Mg, 21-pH, 22-BS, 23-diameter, 24-DBH, 25-volume, 26-Al^{3+}, 27-H^{+}, 28-CEC.)

Reference	**Location**	**Latitude**	**Longitude**	**Biome**	**Stand type**	**Time since harvesting (year)**	**Variable included ***
Ares *et al.* (2007)	USA	46.72	-123.42	Temperate	conifer	1	1
Belanger *et al.* (2003)	Canada	49	-74.5	Boreal	conifer	3	2, 3, 4, 5
Belleau *et al.* (2006)	Canada	48.48	-79.41	Boreal	deciduous	1	2, 3, 4, 5, 6, 7
Brandtberg and Olsson (2012)	Sweden	60.3	16.43	Boreal	conifer	27	2, 6
Carter *et al.* (2002)	USA	30.6	-94.4	Temperate	conifer	3	8, 9
Curzon *et al.* (2014)	USA	44.38	-83.31	Boreal	deciduous	15	10
Egnell and Leijon (1999)	Norway	56.87	15.38	Temperate	conifer	15	1,11, 12
Egnell and Valinger (2003)	Sweden	56.87	15.38	Temperate	conifer	20	1, 11, 12
Fleming *et al.* (2006)	USA, Canada	55.97	-120.47	Temperate	conifer	5	11
Goulding and Stevens (1988)	Scotland	53.02	-4.1136	Temperate	conifer	2	3
Hendrickson (1988)	Canada	45.97	-77.38	Boreal	mixed	4	1, 13
Hendrickson *et al.* (1989)	Canada	45.97	-77.38	Boreal	mixed	3	2, 6

Reference	Location	Latitude	Longitude	Biome	Stand type	Time since harvesting (year)	Variable included *
Johnson *et al.* (2002)	USA	34	-83	Temperate	conifer	16	8
Johnson and Todd (1998)	USA	35.97	-84.28	Temperate	deciduous	15	3, 4, 5, 6, 7
Kaarakka *et al.* (2014)	Finland	61.02	24.69	Boreal	conifer	10	8, 9
Kabzems and Haeussler (2005)	Canada	55.97	-120.47	Boreal	deciduous	5	1, 2, 13
Kershaw *et al.* (2015)	Canada	49	-89.22	Boreal	conifer	15	14, 15, 16
Klockow *et al.* (2013)	USA	47	-92.24	Boreal	deciduous	1	8, 9, 10, 17, 18, 19
Kurth *et al.* (2014)	USA	47	-92.24	Boreal	deciduous	15	8, 9, 10, 17, 18, 19
Laiho *et al.* (2003)	USA	30.88	-92.5	Temperate	conifer	5	8
Li *et al.* (2003)	USA	34.9	-76.82	Temperate	conifer	5	8, 9
Mahendrappa *et al.* (2006)	Canada	46.37	-62.83	Temperate	mixed	11	1
Mann (1984)	USA	35.97	-84.28	Temperate	mixed	1	1, 13
Mattson and Swank (1989)	USA	35.07	-84.43	Temperate	mixed	6.5	2, 8
McInnis and Roberts (1994)	Canada	46	-66.33	Temperate	mixed	2	13
Morris *et al.* (2013)	Canada	49	-89.22	Boreal	conifer	15	1, 10, 13
Norris *et al.* (2014)	Canada	50.22	-119.35	Temperate	deciduous	16	8, 9

Reference	Location	Latitude	Longitude	Biome	Stand type	Time since harvesting (year)	Variable included *
Nykvist and Rosén (1985)	Sweden			Boreal	conifer	14	3, 4, 5
Olsson *et al.* (1996a)	Sweden	56.7	13.83	Temperate	conifer	15	17, 18, 20
Olsson *et al.* (1996b)	Sweden	64.27	19.52	Boreal	conifer	15.5	8, 9
Piatek and Allen (1999)	USA	36.42	-78.5	Temperate	conifer	15.5	6
Proe and Dutch (1994)	England	55.17	-2.5	Temperate	conifer	10	1
Proe *et al.* (1999)	England	55.17	-2.5	Temperate	conifer	5	1
Roberts *et al.* (1998)	Canada	48.98	-56.05	Boreal	deciduous	3	3, 4, 5, 7
Roberts *et al.* (2005)	Canada	46.72	-123.42	Temperate	conifer	2	1
Rothstein and Spaulding (2010)	USA			Temperate	conifer	52.5	8, 9
Saarsalmi *et al.* (2010)	Finland	63.26	28.3	Boreal	conifer	24.5	9, 19
Sanchez *et al.* (2006a)	USA	30.88	-92.5	Temperate	conifer	10	9, 19
Sanchez *et al.* (2006b)	USA	34.92	-76.8	Temperate	conifer	5	8, 9
Sikström (2004)	Sweden	59.83	12.33	Boreal	conifer	5	1, 11, 12
Strömgren *et al.* (2013)	Sweden	64.41	18.31	Boreal	conifer	25	8
Thiffault *et al.* (2006)	Canada	47.315	-71.075	Boreal	conifer	17.5	2, 3, 4, 5, 6
Titus *et al.* (1998)	Canada	36.42	-78.5	Temperate	conifer	2	6

Reference	**Location**	**Latitude**	**Longitude**	**Biome**	**Stand type**	**Time since harvesting (year)**	**Variable included ***
Titus and Malcom (1992)	England	55.13	-2.48	Temperate	conifer	2	6, 7, 9, 19
Vanguelova *et al.* (2010)	England	55.1	-2.3	Temperate	conifer	28	8, 9
Wall (2008)	Finland	61.78	24.75	Boreal	conifer	4	8, 9, 17, 18, 19, 20
Wall and Hytonen (2011)	Finland	62.05	24.2	Boreal	conifer	30	19
Walmsley *et al.* (2009)	England	53.02	-4.1136	Temperate	conifer	23	1, 3, 4, 12, 13
Waters *et al.* (2004)	Canada	51.5	-96.25	Boreal	conifer	3	13
Zabowski *et al.* (2000)	USA	47.85	-120.64	Temperate	conifer	5	1, 11

Reference	**Location**	**Latitude**	**Longitude**	**Biome**	**Stand type**	**Time since harvesting (year)**	**Variable included ***
(Smolander *et al.*, 2015)	Europe	66.792	-27.992	Boreal	conifer	10	1,2,3,4,5,6, 10, 12,21,22,23
(Johnson *et al.*, 2016)	USA	35.98	-84.26	Temperate	mixed	33	1,2,3,4,5, 6,7,8,9
(Foote *et al.*, 2015)	USA	31.108	-95.167	Subtropical	conifer	15	2，9
(Webster *et al.*, 2016)	Canada	47.7	-83.6	Boreal	conifer	40	2，3，7，9
(Zetterberg *et al.*, 2016)	Sweden	56.867	15.383	Boreal	conifer	27	17,18,19,20
(Jurevics *et al.*, 2016)	Sweden	50.03	14.4	Boreal	conifer	36	2,8,10
(Johnson *et al.*, 2016)	USA	34.983	-81.65	Subtropical	conifer	33	1,2,3,4,5,6, 7
(Mushinski *et al.*, 2017)	USA	31.108	-95.166	Subtropical	conifer	21	1,2,6,12
(Egnell *et al.*, 2015)	Finland	64.183	19.66	Temperate	conifer, mixed	24	8,9
(Vangansbeke *et al.*, 2015)	Belgium	51.283	5.567	Temperate	conifer	28	17,18,19,20
(Huang *et al.*, 2011)	New Zealand	-38.23	175.967	Temperate	conifer	20	8
(Huang *et al.*, 2013)	China	26.8	117.967	Subtropical	conifer	15	1,6,10,12,
(Wu, 2017)	China	25.791	116.867	Subtropical	conifer	5	2,3,6,7
(Li, 2011)	China	26.25	119	Subtropical	conifer	16	1,24
(Hu *et al.*, 2013)	China	26.8	117.967	Subtropical	conifer	15	2,6,8
(Kranabetter *et al.*, 2017)	Canada	54.612	-126.307	Boreal	conifer	20	1,11,24
(Morris *et al.*, 2013)	Canada	49.067	-89.4	Boreal	conifer	15	1,24,25
(Fleming *et al.*, 2014)	Canada	47.267	-81.78	Boreal	conifer	15	1,23,24

(Tamminen *et al.*, 2012)	Finland	63.23	28.56	Boreal	conifer	26	2,3,4,5,6,7
(Ring *et al.*, 2016)	Finland	57.147	14.772	Boreal	conifer	5	3,4,5,21,26
(Mendham *et al.*, 2003)	Australia	-34.3	116	Mediterranean	Evergreen-broadleaf	6.5	2,3,4,5,6,7, 25
(Chen & Xu, 2005)	Australia	-26	152.816	Subtropical	conifer	6	2,6
(Zetterberg *et al.*, 2013)	Sweden	56.7	13.67	Boreal	conifer	32	2,3,4,5,6,21,26,27,28
(Nambiar, 2008)	Congo	-4	12	tropical	Evergreen-broadleaf	8	1,9,11,17,18, 19,20,24,25,

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