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Effects of forest management on soil C and N storage: meta analysis

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Abstract

The effects of forest management on soil carbon (C) and nitrogen (N) are important to understand not only because these are often master variables determining soil fertility but also because of the role of soils as a source or sink for C on a global scale. This paper reviews the literature on forest management effects on soil C and N and reports the results of a meta analysis of these data. The meta analysis showed that forest harvesting, on average, had little or no effect on soil C and N. Significant effects of harvest type and species were noted, with sawlog harvesting causing increases (+18%) in soil C and N and whole-tree harvesting causing decreases (−6%). The positive effect of sawlog harvesting appeared to be restricted to coniferous species. Fire resulted in no significant overall effects of fire on either C or N (when categories were combined); but there was a significant effect of time since fire, with an increase in both soil C and N after 10 years (compared to controls). Significant differences among fire treatments were found, with the counterintuitive result of lower soil C following prescribed fire and higher soil C following wildfire. The latter is attributed to the sequestration of charcoal and recalcitrant, hydrophobic organic matter and to the effects of naturally invading, post-fire, N-fixing vegetation. Both fertilization and N-fixing vegetation caused marked overall increases in soil C and N.

Keywords: Harvesting; Fire; Fertilization; Nitrogen fixation; Soil carbon; Soil nitrogen; Meta analysis

1. Introduction

Forest soil scientists have long been concerned with soil carbon (C) and nitrogen (N) because these are often the master variables determining soil fertility (Pritchett and Fisher, 1987). In recent decades, knowledge of the role of soils as a source or sink for C on a global scale has become vital for assessing of changes in atmospheric CO_2 concentrations. Schimel (1995) estimated that soils contain approximately twice as much C (1580×10^{15} g) as the atmosphere (750×10^{15} g) or terrestrial vegetation (610×10^{15} g). Less than 1% of the terrestrial C reservoir (1.9×10^{15} g C per year) is emitted to the atmosphere through changing land use each year, whereas amounts of C entering soil as detritus (61.4×10^{15} g C per year) and leaving by respiration (60×10^{15} g C per year) are far greater (Schimel, 1995). Dixon et al. (1994) estimated that forest ecosystems contain approximately half

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of the total terrestrial C pool (1146×10^{15} g), with two-thirds of this (787×10^{15} g) residing in forest soils. They calculated that changes in forest land cover caused a net input of 0.9×10^{15} g C per year to the atmosphere, the result of a net loss of 1.6×10^{15} g C per year at low latitudes and a net gain of 0.7×10^{15} g C per year at high latitudes. Dixon et al. (1994) do not provide estimates of detritial and respiration fluxes, but these are presumably half or more of the total terrestrial fluxes estimated by Schimel (1995).

Forest soils in North America are of particular interest with respect to the $1.0–2.2 \times 10^{15}$ g C per year that is unaccounted for by the difference between fossil fuel emissions, the increase in atmospheric CO_2, and the estimated oceanic CO_2 uptake. Fan et al. (1998) estimated that North American forests take up 1.7×10^{15} g C per year, the equivalent of 3 to 4×10^6 g C per hectare per year This is well in excess of the average rates of C accumulation in biomass of US forests (1.4×10^6 g C per hectare per year) reported by Dixon et al. (1994), but the rate of C accumulation in forest soils is unknown.

In light of these observations, reliable information is needed on forest soil C pool sizes as well as the effects of management practices on these pools. In a literature review conducted nearly a decade ago (Johnson, 1992), several conclusions were reached regarding cultivation, harvesting, and burning. The review confirmed, for example, that while cultivation leads to substantial decreases in soil C in all but the most C-poor soils, losses of soil C after harvesting and reforestation are negligible. Further, soil C losses may occur following harvesting in tropical soils where recovery after reforestation is apparently quite rapid, and in cases where harvesting is followed by intense broadcast burning. The review found, however, that soil C gains could occur following harvesting due to the incorporation of slash into the mineral soil. In addition, the effects of fire on soil C were found to be highly dependent on fire intensity and the invasion of N-fixing vegetation after fire. Johnson (1992) also concluded that there was a marked trend toward greater soil C with the introduction of N-fixers and fertilization.

A serious problem encountered in Johnson (1992) was the difference in sampling protocols among studies (e.g., number of replicates, sampling depth, time since treatments). The intensity of sampling also varied considerably among studies. Finally, many comparisons were confounded by temporal differences in sampling intervals, which varied from as short as one month to as long as 83 years after treatment. Several of the long-term and chronosequence studies indicated significant temporal trends in soil C. No attempt was made by Johnson (1992) to stratify results temporally.

The objective of this paper is to update the previous review on forest management and soil C with new references, add data on soil N responses, and summarize the entire database using meta analysis. Johnson (1992) included 13 references for harvest effects (doubled to 26 references), 12 references for fire effects (now 13 references), and 13 references for fertilization and N-fixation effects (now 16 references). As before, we omitted O horizons from our analysis. Forest harvesting can cause gains, losses, or no effect on O horizon mass and nutrient content depending on site conditions and site preparation practices. Harvest effects on O horizons are straightforward in the sense that they are directly affected by residue management practices. Longer-term effects, however, are complicated by the legacy of residues (if any) left on site at harvest, the type and condition of these residues (wood or foliage, large or chipped, ploughed or left on surface), the natural decomposition rate of the site, and the rate of new detritus input to the forest floor from regrowing vegetation. The available data on O horizon responses to harvesting was inadequate to assess the importance of these factors; and thus, a direct analysis was not conducted. Rather, O horizon responses were considered as a variable affecting mineral soil C and N via residue management.

Meta analysis was used to determine mean responses of forest soil C and N to different management techniques and to place confidence limits around those means. Meta-analytical methods have been developed for quantitative analysis of research results from multiple independent experiments (Gurevitch and Hedges, 1993; Cooper and Hedges, 1994) and have been used successfully with ecological data (e.g., Curtis, 1996; Curtis and Wang, 1998). These methods usually provide advantages over narrative reviews and quantitative reviews which lack sampling rigor and robust statistical methods (Arnqvist and Wooster, 1995).

Quantitative meta analyses involve the calculation of a treatment effect size (with known statistical properties) that can be averaged across independent studies, giving an overall mean effect size (Arnqvist and Wooster, 1995). Variation in mean effect size can then be partitioned within and among categorical groups. We characterized each study according to the specific harvest treatment, the time since treatment, and the species involved. Factors such as soil texture and climate have well-known effects on soil C and N contents (Post et al., 1982; Oades, 1988) and may play a role in the observed patterns as well. Future analyses of these data could include these and other factors potentially affecting soil C and its response to forest management.

2. Methods

2.1. Meta analysis

A treatment effect size estimator commonly employed in meta analysis is the magnitude of an experimental treatment mean ($\overline{X}_e$) relative to the control treatment mean ($\overline{X}_c$) (Cooper and Hedges, 1994). A typical effect size metric in harvest impact studies is the response ratio, $r = \overline{X}_e/\overline{X}_c$, or the relative impact on, for example, soil C content in a forest plot following some experimental treatment compared to that in control plots. To be useful statistically, r first must be log transformed such that $\mathrm{lr} = \ln(r) = \ln(\overline{X}_e) - (\overline{X}_c)$. If $\overline{X}_e$ and $\overline{X}_c$ are normally distributed and $\overline{X}_c$ is unlikely to be negative, then lr will be approximately normally distributed with a mean approximately equal to the true response log ratio.

Although a more robust meta analysis is possible when studies report means, standard deviations (or standard errors), and number of replicates, many of the studies available to us did not report some measure of variance for the response variables in which we were interested. In this circumstance, and in order to include as many studies as possible, an unweighted meta analysis was used. Mean effect size for each study was calculated, with bias-corrected 95% confidence intervals (CIs) generated by a bootstrapping procedure (5000 iterations) using Meta-Win software (Rosenberg et al., 1997).

An important goal of this meta analysis was to determine whether particular experimental conditions or forest type elicited quantitatively different responses to management. With meta analysis, we can test whether there are significant differences in mean response among categorical groups (e.g., hardwoods or conifers, or time since harvest). In a procedure analogous to the partitioning of variance in analysis of variance, the total heterogeneity for a group of comparisons (Q_T) is partitioned into within-class heterogeneity (Q_w) and between-class heterogeneity (Q_b), such that $Q_T = Q_w + Q_b$. The Q statistic follows a chi-square distribution, with $k-1$ degrees of freedom (Hedges and Olkin, 1985).

2.2. Data sources and calculations

The data set compiled by Johnson (1992) was updated with a second literature review and call for papers and reports through the International Energy Agency's IEA T6/A6 project (Impacts of Forest Harvesting on Long-term Site Productivity). To be included in our analysis, studies had to report pre-treatment data or control plot data and the number of replicates for each. Reporting standard deviations was preferable but not essential. The authors were contacted if certain data were missing (e.g., number of replicates). In all cases where authors were contacted, they responded positively with the needed information (see Acknowledgments). Data Thief® software was used to extract data from figures. Several relevant studies had to be omitted because of a lack of pre-treatment or unharvested control values (e.g., Ballard and Will, 1981; Miller and Sirois, 1986; Fernandez et al., 1989; Jurgensen et al., 1989; Smethurst and Nambiar, 1990b, 1995).

Data on A horizons and whole soils were analyzed separately. Results from studies reporting data on surface soils only, and from papers reporting data from A horizons as well as deeper horizons, were included in the A horizon database. In some cases (e.g., Alban and Perala, 1992), only whole-soil data was reported. The whole soil data base consisted of data on whole soil C and/or N content (to variable depths defined by the individual investigator and generally ranging from 20 to 100 cm). In cases where concentration data by horizon (but not for whole-soil profiles) were reported, a depth-weighted average whole soil concentration (WSC) was calculated using the following equation:

$$\mathrm{WSC} = \frac{\sum(C_D(D))}{\sum D} \tag{1}$$

where D=depth, and C_D=C or N concentration at depth D. A simple weighting by depth was used since changes in bulk density (which usually increases with depth, causing too much weighting of upper horizons) should be offset by changes in percent gravel (which also increases with depth but would cause too much weighting of subsurface horizons). Although calculating absolute content based on these assumptions have resulted in many potential errors, such errors should not have caused bias in the assessment of relative treatment effects, which were based on the ratio of treatment to control values.

For analyses of harvest effects, categorical groups included sawlog (SAW) where only bole material was removed and whole-tree harvesting (WTH) where all aboveground biomass was removed either as whole trees or by removal of residues. Studies which included forest floor removal were included in the WTH category. For analyses of fire effects, the categorical groups included prescribed fire (PF), broadcast burning of slash after harvest (BB), and wildfire (WF). Fertilization (FERT) and the presence of naturally-occurring, N-fixing vegetation (FIX) were treated as broad general categories for this analysis (fertilization was not broken down into types of fertilizer, timing, amount, etc.). Harvested species were split into broad categories of hardwood (HRD) and conifer (CON), and the time since treatment was divided into three categories: 0–5; 6–10 and >10 years. Partitioning of variance among these categorical groups proceeded in two steps: first, between-group heterogeneity (Q_b) for each categorical variable was examined across all data for a given response variable (e.g., soil A horizon carbon content). If no categorical groups showed significant Q_b, there was no statistical justification for subdivision of the data; and the overall mean and confidenc interval (CI) were presented. Second, where significant Q_b was found, the data set was subdivided according to levels of those categorical variables showing significant Q_b, and the first step repeated. Mean log ratios were calculated when the number of categorical variables exhibiting significant Q_b had been reduced to one or zero, suggesting no further partitioning of the data set was justified. Means were considered to be significantly different from one another if their 95% CIs were non-overlapping and were significantly different from zero if the 95% CI did not overlap zero (Gurevitch and Hedges, 1993).

3. Results

3.1. Harvesting

Seventy three observations from 26 publications were included in the harvest effects database (Table 1). Fig. 1 presents an overall summary of these data, shown as a histogram of the number of observations, y-axis) within each effect category (in deciles of percent change relative to control or initial value, x-axis) and the means and 95% CIs of the (back-transformed) response ratios. This summary shows that forest harvesting, on average, had little effect on soil C or N in A horizons and whole soils (the responses

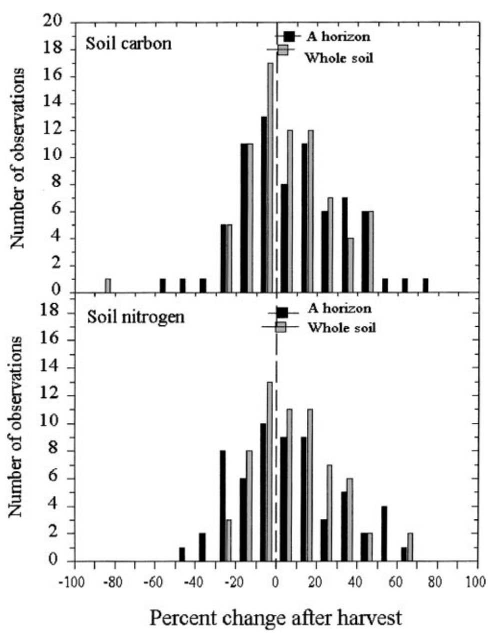

Fig. 1. Distribution of the number of studies showing the effect of harvesting on soil C (top panel) and N (lower panel) in A horizons and whole soils, in deciles of percent change from control. (Mean values and 95% confidence intervals of the back-transformed response ratios are shown in the legend.)

Table 1
References included in harvesting database (73 entries)

Species	Location	Treats[a]	Reference
Populus tremuloides	Alberta	SAW	Alban and Perala, 1992
Mixed conifer	California	SAW	Black and Harden, 1995
Pinus elliottii, P. paulustris	Florida	SAW	Burger and Pritchett, 1984
Pinus contorta	Wyoming	SAW	Debyle, 1980
Pinus radiata	Australia	SAW, WTH	Edmonds and McColl, 1989
Eucalypt/rainforest	Tasmania	SAW	Ellis and Graley, 1983
Eucalypt	Tasmania	SAW	Ellis et al., 1982
Mixed conifer	California	SAW	Frazer et al., 1990
Mixed conifer, hardwood	Ontario	SAW, WTH	Hendrickson et al., 1989
Northern hardwood	New Hampshire	WTH	Johnson, 1995a
Mixed oak	Tennessee	SAW, WTH	Johnson and Todd, 1998
Northern hardwood	New Hampshire	WTH	Johnson et al., 1991
Mixed conifer/hardwood	Japan	SAW	Kawaguchi and Yoda, 1986
Mixed deciduous	North Carolina	SAW, WTH	Knoepp and Swank, 1997
Mixed deciduous	North Carolina	SAW, WTH	Mattson and Swank, 1989
Northern hardwood	Michigan	WTH	Mroz et al., 1985
Picea abies, Pinus sylvestris	Sweden	SAW	Olsson et al., 1996
Northern mixed wood	Canada	SAW	Pennock and van Kessel, 1997
Pentaclethera macroloba	Costa Rica	SAW	Raich, 1983
Mixed conifer/hardwood	Alberta	SAW	Schmidt et al., 1996
P. elliottii	Florida	WTH	Shan and Morris, 1998
P. radiata	Australia	SAW, WTH	Smethurst and Nambiar, 1990a
P. radiata	New Zealand	SAW, WTH	Smith et al., 1994
Populus	Australia	WTH	Stone and Elioff, 1998
Northern hardwood	Wisconsin	SAW	Strong, 1997
P. taeda	South Carolina	SAW, WTH	Van Lear, 1998

[a] SAW: sawlog harvest, where bole only was removed and residue left on site; WTH: whole-tree harvest, where either all aboveground residue was removed or slash was removed after sawlog harvest.

centered on 0% change; and CIs of the mean response ratios overlapped 0). The results of the meta analyses for A horizon data are summarized in Figs. 2 and 3. The overall average percent change in C and N, compared to control or pre-treatment values, was near zero; and the 95% CIs overlap zero, indicating that harvesting had no statistically significant effect on soil C or N across the entire data set. Significant differences were found, however, in the effect on soil C and N among harvest methods, with sawlog harvesting causing significant increases in soil C and N and whole-tree harvesting causing slight decreases (Figs. 2 and 3). The increases in soil C with sawlog harvesting was entirely associated with coniferous species, that is, there was a significant species effect within the sawlog harvest category, with conifers producing more soil C after harvest than hardwoods or mixed stands (Fig. 2). The coniferous species also

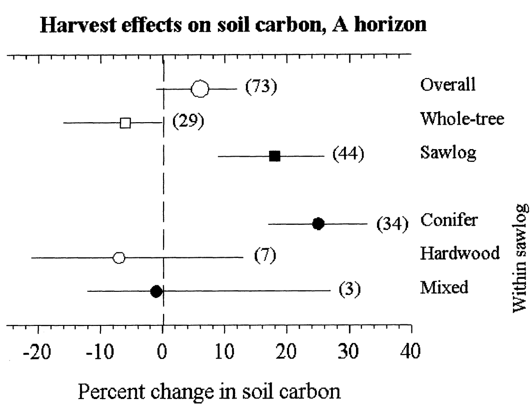

Fig. 2. Plot of A horizon non-parametric meta analysis results for soil C with harvesting. 99% confidence intervals and number of studies (in parenthesis) are shown.

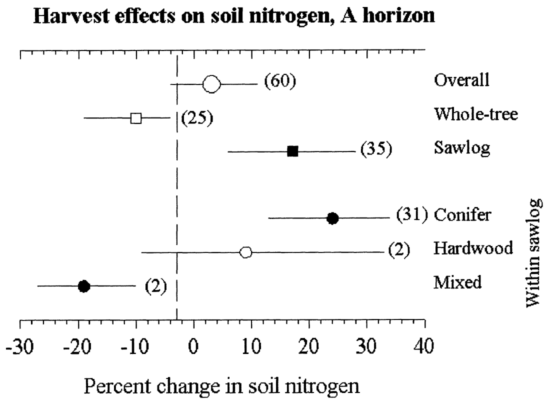

Fig. 3. Plot of A horizon non-parametric meta analysis results for soil N with harvesting. 99% confidence intervals and number of studies (in parenthesis) are shown.

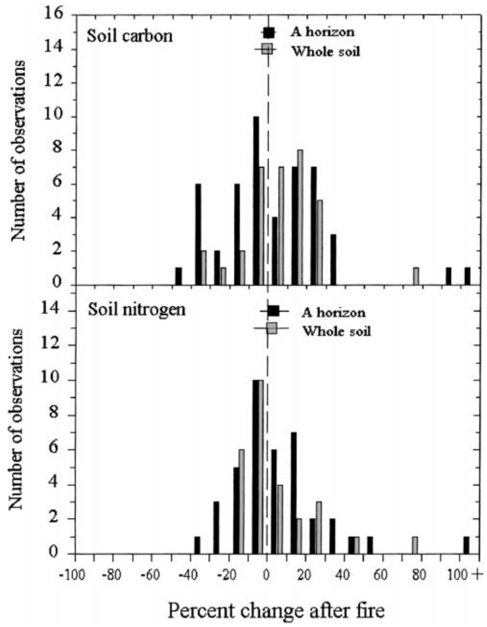

Fig. 4. Distribution of the number of studies showing the effect of fire on soil C (top panel) and N (lower panel) in A horizons and whole soils, in deciles of percent change from control. (Mean values and 95% confidence intervals of the back-transformed response ratios are shown in the legend.)

produced significant increases in soil N after sawlog harvesting whereas hardwoods produced no significant effect, and mixed species produced a negative effect (Fig. 3). There were no significant effects of harvest type, time since harvest, or species on the soil B horizons or on whole-soils, although the overall patterns were similar to those in the A horizons (data not shown).

3.2. Fire

Forty eight observations from 13 publications were included in the fire effects database (Table 2). As was the case in Johnson (1992), the distribution of soil C and N responses to fire was centered around zero both for A horizons and whole soils (Fig. 4). Calculation of mean response ratios and their CIs indicated no

Table 2
References included in fire database

Species	Location	Treats[a]	Reference
P. palustris	South Carolina	PF	Binkley et al., 1992a
Pinus ponderosa	Arizona	PF	Covington and Sackett, 1986
Picea mariana, P. glauca, Betula pendula, P. tremuloides	Alaska	WF	Dyrness et al., 1989
Chaparral	Sardinia	PF	Giovannini et al., 1987
Mixed conifer	Washington	WF	Grier, 1975
Mixed conifer	Montana	PF	Jurgensen et al., 1981
Piñon-juniper	Arizona	PF	Klopatek et al., 1991
Psuedotsuga menziesii, mixed conifer	Washington, Oregon	BB	Kraemer and Hermann, 1979
Sub-boreal spruce	British Columbia	BB	Macadam, 1987
P. taeda, *P. palustris*, *P. elliottii*	South Carolina, Alabama, Florida, Louisiana	PF	McKee, 1982
P. ponderosa	Oregon	PF	Monleon et al., 1997
Eucalyptus regnans	Australia	BB	Rab, 1996
Quercus suber	Algeria	WF	Rashid, 1987

[a] PF: prescribed fire; WF: wildfire; BB: broadcast burned after harvest.

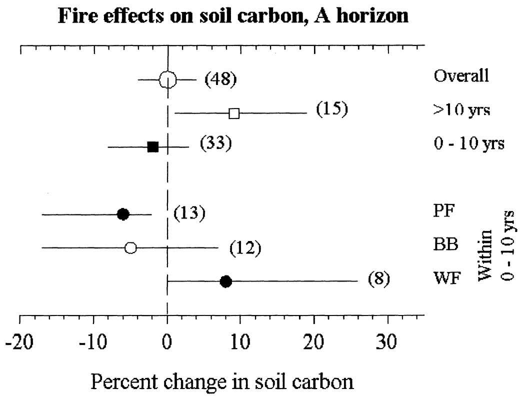

Fig. 5. Plot of A horizon non-parametric meta analysis results for soil C with fire. 99% confidence intervals and number of studies (in parenthesis) are shown. Times 1, 2 and 3 refer to 0–5, 6–10, and 10+ years since treatment; PF: prescribed fire, BB: broadcast burning of slash after harvesting, and WF: wildfire.

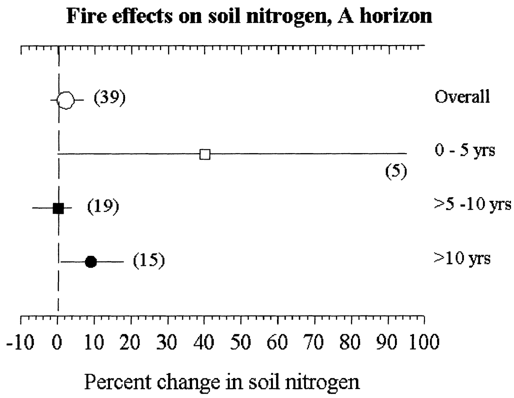

Fig. 6. Plot of A horizon non-parametric meta analysis results for soil N with fire. 99% confidence intervals and number of studies (in parenthesis) are shown. Times 1, 2 and 3 refer to 0–5, 6–10, and 10+ years since treatment.

significant effect of fire on C or N for either A horizons or whole soils (Fig. 4). A significant effect of time since fire was found, with an increase in both soil C and N in the >10 year category but no effect at shorter time intervals (Figs. 5 and 6). When the data for soil C in the 0–5 and 6–10 year categories were combined, there was a significant fire treatment effect, with the counterintuitive result of lower soil C following prescribed fire and higher soil C following wildfire, compared to controls (Fig. 5). The data for B horizons and whole soils showed similar overall trends although there were no significant treatment or time effects (data not shown).

3.3. Fertilization and N-fixing vegetation

Forty eight observations from 16 publications were included in the fertilization and N-fixing vegetation effects database (Table 3). As was found by Johnson (1992), meta analysis on this data revealed that both

Table 3
References included in fertilizer and N-fixer database (48 entries)

Species	Location	Treats[a]	Reference
P. radiata	New Zealand	FERT	Baker et al., 1986
		FIX	
Alnus rubra, P. menziesii	Washington, British Columbia	FIX	Binkley, 1983
Ceanothus velutinus	Oregon	FIX	Binkley et al., 1982
A. rubra, conifer	Oregon, Washington	FIX	Binkley et al., 1992b
Pinus resinosa	Wisconsin	FERT	Bockheim et al., 1986
Acacia, Albizia, Eucalyptus	Hawaii	FIX	DeBell et al., 1985
P. abies	Sweden	FERT	Eriksson et al., 1996
C. velutinus, Pinus jeffreyii	Nevada	FIX	Johnson, 1995b
P. abies, P. sylvestris	Finland	FERT	Mäkipää, 1995
P. elliottii	Florida	FERT	McCarthy, 1983
P. sylvestris	Sweden	FERT	Nohrstedt et al., 1989
E. umbellata, A. glutinosa, J. nigra	Illinois	FIX	Paschke et al., 1989
P. radiata	Australia	FERT, FIX	Smethurst et al., 1986
P. radiata	Australia	FERT	Turner and Lambert, 1986
P. tremuloides	Alaska	FERT	Van Cleve and Moore, 1978
A. rubra, P. menziesii	Washington	FIX	Van Miegroet et al., 1992

[a] FERT: fertilized; FIX: N-fixers either alone in chronosequence, mixed with non-fixers, or adjacent to non-fixers.

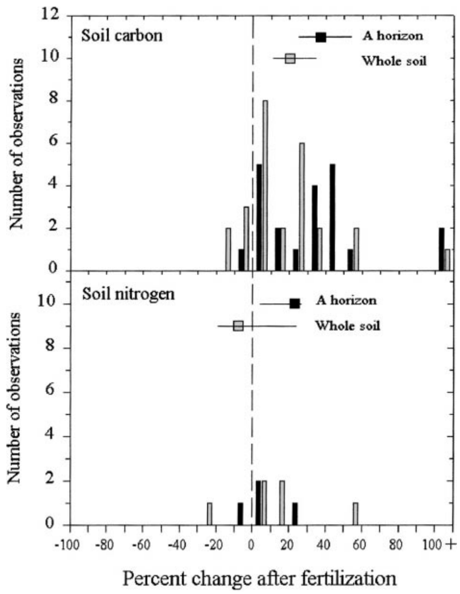

Fig. 7. Distribution of the number of studies showing the effect of fertilization on soil C (top panel) and N (lower panel) in A horizons and whole soils, in deciles of percent change from control. (Mean values and 95% confidence intervals of the back-transformed response ratios are shown in the legend.)

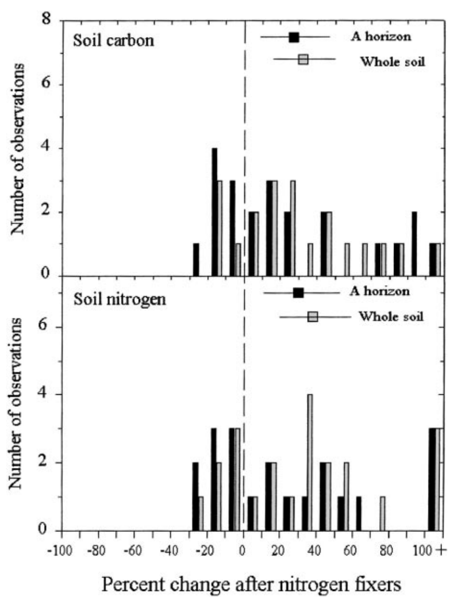

Fig. 8. Distribution of the number of studies showing the effect of N-fixers on soil C (top panel) and N (lower panel) in A horizons and whole soils, in deciles of percent change from control. (Mean values and 95% confidence intervals of the back-transformed response ratios are shown in the legend.)

fertilization and the presence of N-fixers caused a marked positive change in the concentration of soil A horizon C and N (Figs. 7 and 8). Calculation of mean response ratios and their CIs indicated that the effects were statistically significant in all cases except for whole soil N following fertilization (Figs. 7 and 8). There were no significant differences between fertilization and N-fixer effects on A horizon soil C and N, but there was a significant difference in their effects on whole soil N with fertilization yielding lower increases in soil N than N-fixers (data not shown).

4. Discussion

4.1. General patterns of C and N in soils

Several studies, including some not entered into this database because of lack of proper information about control values or number of replications, have demonstrated that residue management after harvesting can have a large effect on mineral soil C and N in coniferous forests (Debyle, 1980; Burger and Pritchett, 1984; Stone and Elioff, 1998; Smethurst and Nambiar, 1990b). These results were obtained in several forest types under a variety of climatic and soil conditions (Table 1) and were reflected by our meta analysis (Figs. 2 and 3). For obvious reasons, the effects of residue management would be especially large for O horizons; however, several publications reviewed in this study found that these effects are not large in mineral soils. Meta analysis suggested that, on average, residue removal (i.e., whole-tree harvest) caused a 6% reduction in A horizon C and N whereas leaving residues on site (i.e., sawlog harvest) cause an 18% increase (compared to controls). The positive effect on soil C and N of leaving residues on site seems to be restricted to coniferous species; several studies from a widely varied set of conditions have clearly shown that residues had little or no effect on soil C or N in hardwood or mixed forests (Hendrickson et al., 1989; Mattson and Swank, 1989; Knoepp and Swank, 1997; Johnson and Todd, 1998). Some studies in coniferous forests also show little or no effect of residues on soil C or N (Olsson et al., 1996; Shan and Morris, 1998).

Several studies indicated that time since harvest is an important variable. In particular, several studies found that soil C and N temporarily increase after sawlog harvesting, apparently a result of residues becoming incorporated into the soil (Kawaguchi and Yoda, 1986; Smethurst and Nambiar, 1990a; Black and Harden, 1995; Johnson, 1995a; Knoepp and Swank, 1997; Pennock and van Kessel, 1997). In some cases, this elevation in soil C and N is short-lived (e.g., less than 4 years for Smethurst and Nambiar, 1990a), whereas in others, it is longer lasting (e.g., at least 18 years for Knoepp and Swank, 1997). Black and Harden (1995) observed that soil C/N ratio provides a signature of the influence of residues: soil C/N is initially elevated because of the incorporation of high-C/N ratio woody residues and later decreases to an equilibrium level as soil C is selectively lost.

The literature includes a mixture of chronosequence studies (e.g., Kawaguchi and Yoda, 1986; Black and Harden, 1995; Pennock and van Kessel, 1997) and repeated sampling studies on the same site (e.g., Smethurst and Nambiar, 1990a; Johnson, 1995a; Knoepp and Swank, 1997; Johnson and Todd, 1998). Questions arise and will always remain as to the comparability of sites among chronosequence studies and about laboratory or sampling bias over time in real-time sampling studies. Even in cases where old samples are retained and re-analyzed, there may be questions about changes during storage (Johnson and Todd, 1998). The general trends found in a number of these studies, however, are consistent with the concept of high C/N ratio residues becoming incorporated into soils over the short-term with soil C re-equilibrating to lower levels and to C/N ratios more similar to background as time passes. This raises other questions regarding C balances. Specifically, what is the long-term fate of the residues? They remain part of the O horizon for long periods in some cool coniferous forests (e.g., Harmon et al., 1990); but in warmer hardwood forests, they rapidly decompose (e.g., Johnson and Todd, 1998). If leaving residues on site has no long-term positive effect on mineral soil C, removing residues for biomass burning may be more C efficient (by offsetting fossil fuel combustion) than leaving them on site (c.f., Johnson and Todd, 1998). Conversely, nutrients left behind in residues may result in long-term carbon gains in aboveground vegetation (c.f., Van Lear, 1998) and cause residue removal to be less C efficient. If the latter is true, how do the C and economic costs of fertilization compare with the costs of leaving residues on site? Our analysis in this study can only provide partial answers to these questions. Indeed, the answers to these questions — while very important to both intensive forestry and the global C issue — surely vary substantially by site and probably defy generalization.

The results of the literature update and meta analysis for fire, fertilization, and N-fixers produce the same conclusions as the previous literature review (Johnson, 1992) on soil C. The effects of fire on soil C and N are very dependent upon fire intensity and time since the fire. During this period, post-fire N-fixers may add substantially to soil C and N pools. Thus, low-temperature fires (e.g., prescribed fire) may cause little initial loss in mineral soil C and N but may result in later gains due to the incorporation of unburned residues (including charcoal) and the influences of N-fixers (Wells, 1971). Hotter fires can cause increases in soil C in subsurface horizons because of the transport of hydrophobic organic matter from surface horizons and subsequent stabilization with cations (Giovannini et al., 1987) as well as by the influence of post-fire N-fixing vegetation over the longer term (e.g., Johnson, 1995b). Although counter-intuitive, it is clear that fire need not necessarily lead to a loss of soil C or N and indeed may cause increases in soil C and N by incorporation of charcoal and hydrophobic organic matter or by the invasion of N-fixing vegetation.

Fertilization and N-fixers both add substantially to soil C and N pools. This is to be expected in the case of fertilization, given the normal increase in primary productivity in nutrient-poor sites that are fertilized (e.g., Van Cleve and Moore, 1978; Turner and Lambert, 1986). Fertilization would not necessarily be expected to produce any increases in soil C in sites where the nutrients added are not growth-limiting unless the fertilizer itself facilitates chemical reactions which tend to cause increases in soil organic matter (i.e., abiotic N incorporation into humus, organic matter association with polyvalent cations; Paul and Clark, 1989). The large effect of N-fixers on soil N is clearly understandable from the perspective of N inputs; however, the increases in soil organic matter often associated with N-fixers is not so easily explained. For example, N fixation by shrubs and herbs with much lower primary productivity than adjacent or control non-fixing vegetation often produces large increases in soil organic C and N (e.g., Woods et al., 1992; Johnson, 1995b). This would seem to require chemical reactions between soil organic matter and N which facilitate C sequestration in soils (Paul and Clark, 1989). The presence of N-fixers, however, does not always cause soil C and N increases. Paschke et al. (1989) found lower soil C and N beneath mixed stands of walnut (*Juglans nigra*) and either Elaeagnus (*Elaeagnus umbellata*) or alder (*Alnus glutinosa*) than beneath stands of pure walnut. This counterintuitive result appeared to be related to the higher rates of microbial mineralization in the mixed stands.

5. Summary and conclusions

A review of the literature and meta analysis of the data therein showed that forest harvesting, on average, had little or no effect on soil C and N. Significant effects of harvest type and species were found, with sawlog harvesting causing increases (+18%) in soil C and N and whole-tree harvesting causing decreases (−6%). The positive effect of sawlog harvesting appeared to be restricted to coniferous species, although reasons for this are not clear. No significant overall effects of fire on either C or N were found, but there was a significant effect of fire on both soil C and N after 10 years. Meta analysis also indicated a significant fire treatment effect, with the counterintuitive result of lower soil C in prescribed fire and higher soil C in wildfire. The latter was attributed to the sequestration of charcoal and recalcitrant, hydrophobic organic matter and to the effects of post-fire N-fixers.

Both fertilization and naturally-invading, N-fixing vegetation caused marked overall increases in soil C and N. No differences between fertilization and N-fixers on soil C were found, but N-fixers caused greater soil N accumulation than did fertilization.

The conclusions of this study are similar to those reached in a previous literature review on the effects of forest management on soil C which included only half the references (Johnson, 1992). Meta analysis contributed greatly to the review and assessment of forest management effects on soil C and N. Meta analysis allowed us to overcome some of the problems with the data sets reviewed (in terms of replication) and to examine the influences of time, species, and treatment in a rigorous fashion.

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