EFFECTS OF FOREST MANAGEMENT ON SOIL CARBON STORAGE

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ABSTRACT. The literature on soil C change with forest harvesting, cultivation, site preparation, burning, fertilization, N fixation, and species change is reviewed. No general trend toward lower soil C with forest harvesting was apparent, unless harvesting is followed by intense burning or cultivation. Most studies show no significant change (± 10%) with harvesting only, a few studies show large net losses, and a few studies show a net gain following harvesting. Cultivation, on the other hand, results in a large (up to 50%) loss in soil C in most (but not all) cases. Low-intensity rescribed fire usually results in little change in soil C, but intense presribed fire or wildfire can result in a large loss of soil C. Species change can have either no effect or large effects on soil C, depending primarily upon rooting patterns. Fertilization and (especially) nitrogen fixation cause increases in soil C in the majority of cases, and represent an opportunity for sequestering soil C and causing long-term improvements in site fertility.

1. Introduction

Forest soil scientists have,until very recently, paid little attention to soil C relative to other nutrients, even though the role of soil organic matter in soil fertility (cation exchange capacity, structure, bulk density, N, P, S, and water status) is well recognized (Jurgensen et al 1989). Evaluations of the effects of harvesting, burning, and site preparation on forest productivity have concentrated upon nutrient losses and gains with much less attention given to soil organic matter (e.g., Marion, 1979; Boyle et al 1973; Johnson et al 1982, 1988b).

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With the recent concerns over increases in atmospheric CO_2 levels and global warming, forest soil scientists have an additional reason to consider changes in soil C as affected by management practices.

Even a cursory review of published global C budgets reveals that soils could be either a major source or sink for C. For example, the global C budget in Figure 1 indicates that net annual release of C as CO_2 from fossil fuel combustion is 5.3 x 10^{15} g yr-1, whereas detrital inputs to the soil are estimated at about 60 x 10^{15} g yr^{-1} and decomposition at 50 to 60 x 10^{15} g yr^{-1} (Harrington, 1977; Post et al 1990). Clearly, a slight imbalance (10%) between detrital production and decomposition could either equal (if negative) or offset (if positive) the fossil fuel contribution. There is no a priori reason to suspect that litter and soil organic matter are in a steady-state condition or even within 10% of such a condition at present, especially in view of the large changes in land use patterns that continue to occur at a global scale.

A recent analysis by Tans et al (1990) suggests that the terrestrial ecosystems of the Northern Hemisphere are absorbing 2 to 3.4 x 10^{15} g yr^{-1} of C. This amount of C is not otherwise accounted for, and could easily be sequestered within either vegetation or soils. Thus, it is important to gain a better understanding as to whether soils are a net source or a net sink of C, and, if possible make some estimate as to the magnitude of the imbalance between inputs and outputs of C to the soil. While calculations of the latter have been made (e.g., Mann, 1986; Schlesinger 1990), little is known about the error bounds surrounding such estimates; uncertainties may well be so large as to make even the overall direction of change questionable.

There have been several papers suggesting that aboveground biomass in forest ecosystems has been either a significant sink (Delcourt and Harris, 1980) or source (Houghton et al 1983; Harmon et al 1990) of C. Much less information is available on changes in C content of forest soils, and the existing literature is contradictory. Delcourt and Harris (1980) assumed that clearing and cultivation caused a 40% reduction in soil C in the southeastern U.S. In their global C model, Houghton et al (1983) assume 35, 50, and 15% losses of litter and soil C after forest clearing in tropical, temperate, and boreal forests, respectively, and a further delayed loss to 50% of original C content with cultivation. In a later paper on the C balance of Latin American forests, Houghton et al (1991) assumed that cultivation resulted in a 25% loss of soil C, whereas "Logging was assumed not to change the storage of organic carbon in soil." (p. 183). Based upon a review of the literature on tropical forest clearing, Detwiler (1986) concluded that clearing and burning alone do not cause a loss of soil C, and in some cases, may cause a gain. He notes that while clearing followed by cultivation or pasturing cause losses of soil C, "... the decrease in soil carbon is a result of the soil's use, not its clearing" (p.

75). In the absence of hard information on changes in soil C following harvesting, Harmon et al (1990) apparently took a conservative approach by assuming no change; however, they indicate that this assumption is likely false and that, "soil organic matter ... will most likely decrease under intensive management". Schlesinger (1990) analyzed chronosequence studies for soil C accumulation rate, and concluded that, on a worldwide basis, only approximately 0.4 x 10^{15} g C yr^{-1}, or 2.4 g $m^{-2}yr^{-1}$ is stored. Musselman and Fox (1991) quote estimates of 52.5 x 10^{15} g of C stored in U.S. forests, with 59% of this (31 x 10^{15} g) stored in the soil. After accounting for long-term storage of harvested wood, they estimate C lost to the atmosphere from trees to be 6.7 x 10^{15} g of C. For soils, they assume a 25 to 50% loss of C after harvest, which converts to 8 to 15 x 10^{15} g of soil C.

The objective of this paper is to review the literature on forest management with special attention to effects on soil C. It was assumed that, in addition to those few papers which actually highlight soil C changes, a great deal of information on soil C change with management was contained within publications and reports that focused on other nutrients. With the assistance of the International Energy Agency's IEA T6/A6 project ("Impacts of Forest Harvesting on Long-term Site Productivity", W.J. Dyck, Project Leader) letters were sent to foresters, soil scientists and ecologists throughout the world asking for such information. Over 100 reprints were received, most of which are summarized in this document. The reprints were divided into seven categories for the purpose of this report: 1) Harvesting, 2) Cultivation 3) Site Preparation, 4) Burning, 5) Species Conversion, 6) Reforestation and Succession, and 7) Fertilization (including N-fixation).

2. Methods and Materials

Several significant difficulties and uncertainties were encountered while trying to synthesize the literature on forest management and soil C. The question of how to report the data arose immediately: the use of absolute values of soil C would tend to minimize the importance of changes in soils with inherently low C whereas the changes in soils with large soil C would be emphasized. Changes in soils with low C may be of less importance to global C budgets than changes in soils with high C, but low C soils are of equal if not greater interest in terms of changes in site fertility. Converting the results to percentages results in the opposite effect, i.e., emphasizing the results in low C soils, perhaps unduly, in view of their significance to global C budgets. However, the advantages of converting percentages were deemed to outweigh the disadvantages; also, much of the literature on global C deals with changes in soil C on a percentage basis (e.g., Houghton et al 1983; Mann 1986; Musselman and Fox 1991).

One of the most serious problems encountered in summarizing the literature was the differences in sampling protocols, both in space and time. For example, how does one legitimately compare percent changes in C in the top 2 to 5 cm of soil reported by some authors (e.g., Ellis and Graley 1983) with percent changes in the top meter of soil reported by other authors (e.g., Johnson et al 1991)? In order to try to standardize the depth effect somewhat, the percentage changes for the entire soil profile sampled were calculated when not reported.

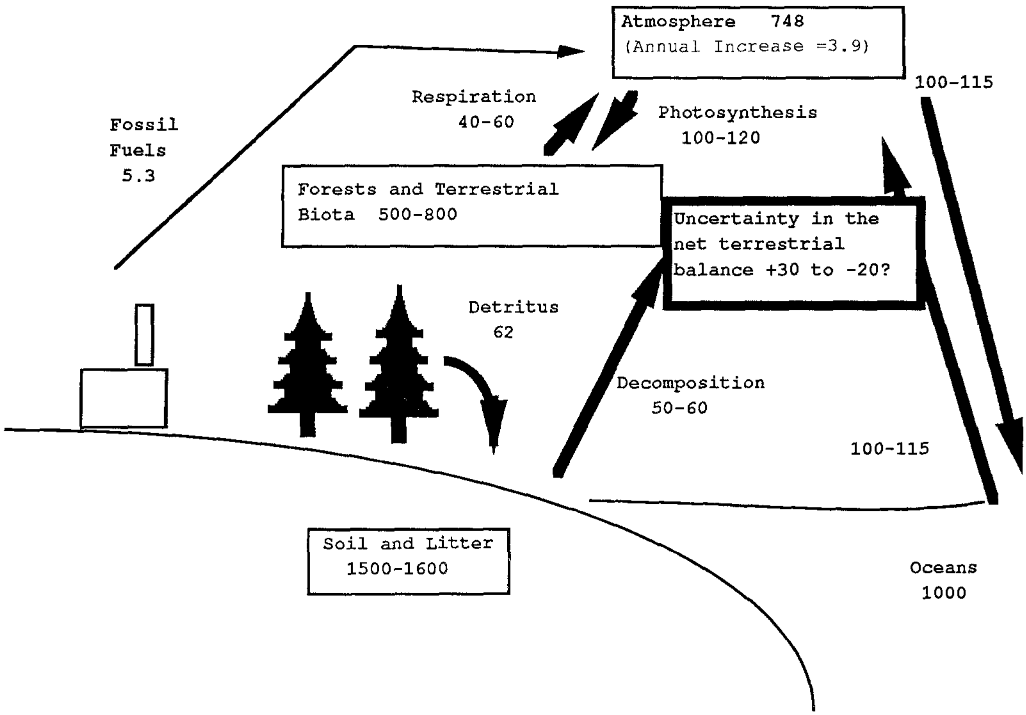

Figure 1. The global C balance. Units are in 10^{15} g y^{-1}. Adapted from Harrington 1987 and Post et al 1991.

Where available, data on bulk density and percent gravel were used for these calculations, but if these data were not available, a total profile soil C concentration value was calculated by depth weighting, i.e., total profile C = Σ(%C x depth)/ Σdepth. This procedure biases the values toward surface horizons, which generally have lower bulk densities and would therefore be given a lower weighting if bulk density data were available for the calculations. Additional sources of bias and error include differences in total soil sampling depth and unrecorded changes in bulk density (Detwiler 1986).

The intensity of sampling varied considerably among these studies; the intensity of sampling in the Hubbard Brook studies reported by Johnson et al (1991) was sufficient to detect statistical significance in a mere 8% change in soil C, whereas in other cases, differences of 20 to 50% were not statistically significant (e.g., Edmonds and McColl 1989; Mattson and Swank 1989). All changes that could be calculated are reported here, along with statistical significance or lack of it, in an attempt to detect overall patterns across sites. The alternative - to assume that no changes in soil C occurred - was deemed to be potentially more misleading than reporting actual changes, in that differences which were significant at any level up to 89% (or more, depending upon the level of significance selected) would be ignored. While the absence of statistical analyses normally negates the value of any particular study, it was reasoned that a collection of data points showing an overall trend would provide useful information, even though each data point in itself may not be particularly significant. An appropriate statistical analogy would be a regression equation, where no statistics are normally available for each point, but the collection of several points may show a meaningful trend.

Finally, many comparisons are confounded by temporal differences. Sampling intervals varied from as short as 1 mo to as long as 83 yr after treatment, and several of the long-term and chronosequence studies indicated significant temporal trends in soil C (e.g., Jenkinson 1970; Durgin 1980; Gholz and Fisher 1982). At this stage, no attempt has been made to stratify the results temporally, given the paucity of data, but potential and documented temporal variations add a significant caveat to the following summaries.

3. Results and Discussion

3.1 HARVESTING

Several studies reported soil C changes with harvesting, either alone or in combination with other treatments. For our purposes here, harvesting alone will be considered separately from harvesting with other treatments in order to avoid confusion as to what the actual effects of harvesting versus other treatments are. This is an especially important consideration when harvesting is followed by cultivation, as will be shown later.

The results of thirteen studies which considered harvesting alone are summarized in Table 1. As one would expect, harvesting alone had a significant effect upon forest floor mass, causing either increases or decreases, depending upon how much slash was left behind. The effects of harvesting on mineral soil C varied from site to site, with reports of increases, decreases, or no effects. However, the majority of the studies reported either no effects or very small changes (<10%; Table 1). The two exceptions occurred in the studies of a tropical rain forest in Ghana (Cunningham 1963) and those in a Eucalypt forest in Tasmania (Ellis and Graley 1983). Cunningham reported soil C reductions that related to the degree of shading and, presumably, soil temperature, after harvesting a tropical rain forest in Ghana. Three yr after harvesting, he noted 57, 49, and 25% decreases in soil C in the 0 to 5 cm depth with full exposure, half-exposure, and full shading, respectively. The same basic pattern held in the 5 to15 cm depth, also (30, 25, and 17% decreases in full exposure, half-exposure, and full shading, respectively). Ellis and Graley (1983) report data indicating a statistically significant (i.e., non overlapping 95% confidence intervals) 23% difference in 0 to 2 cm layer soil C between harvested and unharvested Eucalyptus sites in Tasmania. However, no significant differences were noted in deeper horizons, and the authors did not regard the surface soil differences to be of any real consequence. Thus, the overall effects of harvesting on soil C in this case, also, were actually quite small.

3.2 CULTIVATION

Mann (1985, 1986), Detwiler (1986), and Schlesinger (1986) have provided excellent reviews of the effects of cultivation on soil C. In one of her two papers, Mann (1985) utilized data from 303 loess-derived soil profiles, mostly Alfisols and Mollisols, in the central U.S., and in another paper (Mann 1986) she reviewed the results of 50 studies in the literature involving comparisons of 625 profiles. These comparisons involved both forested and prairie ecosystems, and results were not separated by these two categories. In both cases, she noted that cultivation resulted in a substantial net loss (at least 20%, mostly in the plough layer) in soils that were initially relatively high in C, but a slight net gain (e.g., 11% in Udolls of the central U.S.) in soils that were initially low in C. Using a computer model of land use changes in the tropics, Detwiler (1986) estimated that clearing followed by cultivation results in an average 40% loss of soil C, and clearing followed by pasturing results in an average 20% loss of soil C, each within 5 yr. Schlesinger summarized the effects of clearing and cultivation on soil C from several studies in the literature, and obtained an average loss of 21%, with a range of +1 to -69%.

Table 2 summarizes the reviews by Mann (1985, 1986), Detwiler (1986), and Schlesinger (1986), as well as several other studies that

Table 1. Effects of harvesting on soil C.

Location and species	Treatments	Results	Reference
Hubbard Brook, NH (Northern hardwoods)	Whole -tree harvesting	At 3 yr, 16 to19% loss in LOI in O horizons, 8% loss in E horizon, no change in B. There was a loss in Oi mass, but only 1% change (increase) in total profile organic matter.	Johnson et al 1991
La Selva, Costa Rica (tropical rain forest)	Mature forest vs secondary forest cut 1, 6, and 17 yr previously	Soil C was 8% lower in secondary forest	Reich 1983
Challenge Forest, CA (Mixed conifer)	Chronosequence 100 yr-old, clearcut 6 and 18 yr ago	6-yr-old site had 23 and 35% more total C than 100-yr-old in 0-70 and 70-140 cm, resp., 18-yr-old had 12% less in 0-70 cm, no difference deeper. (No statistics.)	Frazer et al 1990
Klamath Mts. OR (Pseudotsuga menziesii)	Clearcut 20 years previously	1% greater OM in clearcut	Aztet et al 1989
Ghana (Tropical rain forest)	Clearcut, including different degrees of artificial shading	After 3 yr, 57 and 30% decrease in 0-5 and 5-15 cm (resp.) in full exposure, 49 and 25% in half-exposure, 25 and 17% in shade. N losses slightly less.	Cunningham 1963
Hubbard Brook, NH (Northern hardwood)	Whole-tree harvest	30% increase in forest floor, 8% increase in soil after three years (non-significant)	Huntington and Ryan 1990 (same study as Johnson et al 1991)
Petawawa, Ontario (Mixed conifer, hardwood)	Whole-tree (WTH) vs conventional harvest (CH)	Increase in both forest floor (20%) and top 20 cm of soil (18%) with CH; no significant change in forest floor (-2%), but increase in top 20 cm of soil (14%) with WTH	Hendrickson et al 1989

Coweeta, NC (Mixed deciduous)	Whole-tree (WTH) vs bole only (BO)	20% greater C in BO soil, 74% greater C in WTH soil, but may be due to natural, pre-treatment variation	Mattson and Swank 1989
Michigan (Northern hardwood)	Whole-tree harvest on sites of varying quality	40-70% loss in forest floor. No soil data, but soil N changes from +50% to -60%. No statistics	Mroz et al 1985
Minnesota (Populus tremuloides)	Stem-only and whole-tree harvesting	1-2 % increases (non-significant)	Alban and Perla 1990
Tasmania (Mixed Eucalyptus, rainforest)	Clearcut	20% loss in surface 10 cm; not considered significant to site productivity	Ellis and Graley 1983
Australia (Pinus radiata)	Comparison of 4-mo 5 yr-old, and 45-yr-old clearcut	Compared to 45-yr-old, 4-mo-old site had 22% greater soil OM; 5-yr-old site had 20% greater soil OM (not stastically significant)	Edmonds and McColl 1982, 1989
Maine (Mixed hardwood, conifer)	Biomass harvest	At well-drained site, average change of -3% (not significant); at poorly-drained site, average change of -39% (significant in one of 4 horizons only)	Fernandez et al; 1989

Table 2. Effects of cultivation on soil C.

Location	Treatments	Results	Reference
303 sites in central US	Cultivation of either prairie or mature forest	28% overall decease in Udalfs, 11% increase in Udolls	Mann 1985
625 sites worldwide	Cultivation	20% decreases in 20 yr in sites initially in C, slight gain in low C sites	Mann 1986
USA, Central and South America, Africa, India, Thailand, New Guinea	Clearing and Cultivation	Average of 21% loss of soil C, range of +1 to -69%.	Schlesinger 1986
General Tropical Forests	Clearing followed by cultivation or pasturing (estimated from model)	Average loss of 40% soil C with cultivation, 20% with pasturing. No change with logging.	Detwiler 1986
Nigeria (20 sites)	Clearing and cultivation	In most cases, cropping caused decreases in soil C (10 to 50%); increases (10-40%) when crop residues returned to soil	Ayanaba et al 1976
British Columbia Washington (60 sites)	Clearing and cultivation	20% soil C decrease in 35 yr, mostly in first 15 yr.; C:N ratio narrowed from 15:1 to 12:1	Goldin and Lavkulich 1990
Brazil	Clearing and cultivation	Changes after 1 yr difficult to determine because of variability (>50%)	Tiesson and Santos 1989
North Carolina	Tillage; replacement of grasses by annual herbs	24% reduction in total C, mostly (76%) due to reduction in roots.	Richter et al 1990

Indonesia	Shifting cult., conversion to 2° forest, pine plantation and grassland	13-yr-old pine plantation was ~15% lower, grasslands were ~20% higher than natural forest. 2° forest the same as natural forest.	Arimatsu 1983
U.S.A. and tropics	Forest clearing, cropping	0-50% decrease, most in high C soils. 50% greater loss in old soils in tropics than in temperate or young tropical soils	Allen 1985
Peru	Slash and burn, bulldozer clearing with straight and shear blade then cropped with and without fertilizer	No change with slash and burn, approx. 20% reduction with bulldozing at 3 mo. Bedding and fertilization resulted in approx. 15% increase	Alegre and Cassel 1986
Brazil	Pasturing (Chronosequence)	Apparent 20-25% loss of soil C during first 1-2 years followed by increase to forest levels after 8 years as grass roots incorporate into humus.	Cerri et al 1991
Brazil	Pasturing (Chronosequence)	No clear pattern; rapid loss during first year, then gain during 2-6 years, then loss again after 12 years. Spatial variability may confuse results.	Eden et al 1991
Brazil	Cultivation	10-20% loss of soil C; also mobilization of fulvic acids and attendant degradation of soil structure and permeability.	Martins et al 1991
Ghana	Clearing, burning different types of cultivation including "local practice"	Soil C was 13 to 30% higher after clearing and burning in experimental treatments but not in "local practice". After 2 yr, soil C declined by 6% with "local practice" and 20 to 35% in other treatments	Nye and Greenland 1964

were not included in these reviews. The additional papers generally confirm earlier conclusions as to the effects of cultivation: soil C changes ranged from a slight gain to over 50% loss. One study worthy of particular mention is that of Richter et al (1990) who point out the importance of accounting for root biomass when evaluating soil C change. They found a 24% overall decrease in soil after 7 yr of annual tillage of a Udalf in Michigan, and that 76% of this decrease was due to a reduction in root biomass associated with a transition from grasses to annual herbs.

3.3 SITE PREPARATION

The effects of site preparation prior to establishment of a new forest plantation on soil C can be quite considerable, as seen in Table 3. However, the implications for global C budgets are often unclear, in that it is frequently not possible to separate soil C lost by displacement (e.g., bulldozed into slash piles and therefore not necessarily lost to the atmosphere as CO_2) and that which is lost due to decompositon. In general, there is a net loss of soil C with site preparation, the magnitude of which is dependent upon the severity of the disturbance. In that site preparation occurs only once during a forest rotation, one would expect that its overall effects on soil C loss would be less than that of continuous cultivation, however. In cases where site preparation involved incorporating logging residues into the soil, soil C values can obviously be expected to increase (e.g., Smethurst and Nambiar, 1990a). Thus, the effects of site preparation on soil C varied not only with site but with treatment. For instance, Morris and Pritchett (1983) found that only slight changes in mineral soil C due to site preparation (chopping, burning, KG-blade, disking, and bedding) in one Florida slash pine site, whereas Burger and Pritchett (1984) found significant (20-40%) reductions in soil C following site preparation (burning followed by chopping and burning followed by windrowing, disking, and bedding) in another Florida slash pine site (Table 3).

Finally, in a more unusual study, Laine and Vasander (1991) evaluated the effects of drainage and forest establishment upon the C balance of a peat bog in Finland. They found an overall ecosystem C increase of 9% due to increases in tree, litter, and peat C. They concluded that the effects of the increased productivity due to forest establishment more than compensated for any loss of peat C due to increased decomposition rate.

3.4 BURNING

The literature on burning included both prescribed burning and wildfire. The effects of burning upon both forest floor and soil C were very dependent upon fire intensity, as is to be expected. Prescribed

Table 3. Effects of forest site preparation on soil C.

Location and species	Treatments	Results	Reference
Golden Triangle, ME (Mixed hardwood)	Chopped (CH), raked (RK) windrow burned (WB)	Consistent decreases in O horizons; increases of 139, 38, and 69% with CH, RK, and WB in well-drained site, increases of 39, 17, and 11% in poorly-drained site. Changes stastically significant in only 3 of 14 horizons.	Fernandez et a; 1989
Finland (Pinus sylvestris)	Peatland drainage	9% increase overall in drained land due to increase in bulk density, %C and trees.	Laine and Vasander 1991
Mississippi (Pinus spp.)	Skidding vs skyline logging	OM up to 50% lower with severe disturbance, due to displacement. Real losses not known	Miller and Sirois 1986
Florida (P. eliottii)	Burning, low- and high-intensity site prep. at 2 sites (Cary and Bradford)	At Cary, 27% increase with minimal disturbance 20% decrease with intensive disturbance. At Bradford, no change with minimal disturbance 15% decrease with intensive disturbance	Morris and Pritchett 1983
New Zealand (Pinus radiata)	Harvesting, root-raking, burning	Displacement of considerable N, and, presumably C, by soil removal (3-18 cm) during root raking. No idea of actual total C lost to atmosphere.	Sims et al 1988
New Zealand (P. radiata)	Litter raking	No significant differences in 0-5 cm, but 23 and 15% lower in raked plots in 5-10 and 10-10-20 cm levels after 16 yr	Ballard and Will 1981
Australia (P. radiata)	Slash and litter intact (SL), slash removed (L), litter ploughed (LP), and slash and litter removed (SLR)	At 4 mo, 0-15 cm: relative to SL: L= -5%, LP= +53%, SLR = +8%. At 48 mo, all treatments decreased by 14-25% , and relative to SL: L = -7%, LP = +33%, SLR = +7%. No significant effects in 15-30 cm depth.	Smethurst and Nambiar 1990a

Florida (P. eliottii)	Clearcut and burn, then chop vs windrow and bed	At 2 yr, 54% lower C concentration with burning and chopping, 68% lower C with windrow and bedding. Contents (Mg/ha) were 21 and 40% lower, resp.	Burger and Pritchett 1984
Australia (P. radiata)	Windrow and plough	Continuous monitoring of surface soil (unspecified depth) showed decrease of approx. 40% over 42 mo.	Smethurst and Nambiar 1990b

fire usually caused a reduction in 0 horizon weight (Table 4), but either no change or an increase in mineral soil C. Often, the invasion of N-fixing species after burning caused an increase in soil C over the long-term. Kraemer and Hermann (1979) found no significant differences in soil organic matter 25 yr after broadcast burning in 34 plot pairs in western Washington and Oregon. They did, however, find a significant increase in soil C in sites occupied by N-fixing Ceanothus. Wells (1971) reported the results of a 20-yr study of prescribed burning at the Santee forest in South Carolina. Treatments included annual summer burning (AS), annual winter burning (AW), periodic (4 times) summer burning (PS) and periodic winter burning (PW). He found forest floor reductions to be as follows: AS>AW>PS>PW. However, there was a tendency for the forest floor to regain this organic matter over time and approach the control condition in the periodically-burned plots. He also found that during the first 10 yr of the study organic matter and N increased in the top 5 cm of soil in approximately the same order as forest floor was lost. Thus, "the principal effect of burning was the redistribution of the organic matter in the profile and not in any reduction" (p. 88). One treatment (annually-burned plots) showed especially large increases in soil N (550 to 990 kg/ha) during the second 10 yr of the study, which were attributed to increased activity of N-fixers.

McKee (1982) summarized the results of several prescribed burning studies throughout the southeast (including Wells' study) and concluded that burning generally resulted in a decrease in forest floor but an increase in soil C in the top 5 to 10 cm within the first 10 yr, the result being a small net overall system C loss. The causes of the increase in surface soil following prescribed burning likely include incorporation of charcoal and partially burned organic matter into the mineral soil and, in some cases, the increase in the presence of N-fixing species following burning.

In contrast to these studies of low-intensity prescribed burning, other studies of the effects of high-intensity burning (either prescribed or wildfire) show significant soil C loss. Sands (1983) reported that 24 yr after an intense broadcast burn in a Radiata pine site in Australia, soil C was approximately 40 to 50% lower throughout the profile (to a 60 cm depth) than in an unburned plot. Grier (1975) noted a 40% loss of litter and soil N after an intense fire on the eastern slope of the Cascade Mountains of Washington. Neither organic matter nor C changes were reported by Grier, but were presumably quite high, also.

Not all wildfires result in a reduction in soil C, however. Fernandez et al reported large losses of 0 horizon but no significant change in mineral soil C 1 yr after a wildfire in Maine. Dyrness et al (1989) sampled soils within one week of a wildfire in interior Alaska and found that organic matter losses from the forest floor (assessed by comparing to unburned areas) varied from 5 to 80% depending upon

Table 4. Effects of burning on soil C.

Location and Species	Treatments	Results	Reference
Australia (Eucalyptus)	Clearcut and burn (CF2); regular fire over 40 yrs (RB40); and control (C)	No significant difference between RB40 and C; CF2 was 25-43% lower than C	O'Connell 1987
Tasmania (Mixed Eucalyptus, rainforest)	Broadcast burning	Approximately 50% loss in top 10 cm with harvesting and burning, mostly in top 2 cm. Overall effect of burning seen as beneficial	Ellis and Graley 1983
Australia (Eucalyptus)	Prescribed fire once only, 1 month 3 yr, and 19 yr previously	No differences in sites newly burned or burned 3- or 19 yr previously	Edmonds and McColl 1982
South Carolina (P. plaustris)	Prescribed, 1,2,3, and 4-yr intervals	Reduction in O horizons; no effect in mineral soil	Binkley et al in press
Australia (P. radiata)	Intense broadcast burning	40-50 % reduction to 60 cm depth	Sands 1982
Washington (Mixed conifers)	Wildfire	40% loss of forest floor and soil N (No C data given)	Grier 1975
Alaska (Picea glauca, Picea mariana, Betula papyrifera, Populus tremuloides)	Wildfires of varying intensity	Loss of forest floor increased with intensity; losses (up to 15%) gains, (up to 15%), or no change in mineral soil, depending upon intensity and forest type.	Dyrness et al 1989
Maine (Mixed hardwoods, conifers)	Wildfire	Large reduction in O horizon, no effects in mineral soil one year after fire.	Fernandez et al 1989

Santee, SC (Pinus taeda)	20-yr results of annual and periodic (7 yr) burns	Little effect of periodic burns on either O or mineral soil. Annual burning decreased O and increased surface mineral soil C (30%)	Wells 1971
Oregon and Washington (Conifers)	Broadcast burning (Morris plots)	Burned plots 26% higer in OM in north Cascades, 2% lower in south Cascades (Not stastically significant). Increased with Ceanothus noted	Kraemer and Hermann 1979
British Columbia (P. contorta, Picea glauca x engelmannii)	Broadcast burning	Slight decrease (20-30%) at 9 mos, but increase again (40-70%) at 21 mos	Macadam 1987
Brewerton, AL (Pinus palustris)	Biennial winter prescribed fire	After 5 fires, burned = 4% greater than control (not significant)	McKee 1982
Olustee, FL (Pinus elliottii)	Periodic (4-yr) winter (PW), annnual winter (AW) prescribed fire	At 20 years, PW = 17% greater (significant at 95%) AW = 16% greater (not significant) than control	McKee 1982
Roberts, LA (Pinus palustris)	Annual winter prescribed fire	After 65 years. burned was 7% greater than control overall, but lower in surface 5 cm (not significant)	McKee 1982
Santee, SC (Pinus taeda)	Annual winter (AW) , annual summer (AS) periodic (7 yr) winter (PW) and periodic summer (PS) prescribed fire. (Same site as Wells 1971)	PW = -16%, PS = +6%, AW = +11%, AS = +28% relative to control at 30 yr. Only AS was significant, and only at 30-50 cm depths	McKee 1982

fire intensity. Changes in the top 5 cm of mineral soil ranged from +16 to -18% depending upon fire intensity.

3.5 SPECIES CHANGE OR COMPARISONS

Many of the studies dealing with species changes or comparisons involved N-fixers. These results have been lumped together with fertilization for the purposes of this review and are discussed below. Species change studies involving non-N fixers are summarized in Table 5.

The effects of tree species on soil C was often significant but inconsistent. For instance, Turner and Kelly (1985) and Turner and Lambert (1988) compared soil properties beneath planted radiata pine (Pinus radiata) and native Eucalyptus forest at various sites in New South Wales (NSW), Australia. In some cases, they noted greater (average of 35 to 57%) soil C in pine plantation than in the native Eucalyptus forest, in some cases they noted the reverse, and in other cases they found no differences (Table 5). The authors noted that organic matter was the main soil property that was affected by plantation establishment in their study and other related studies.

Gilmore and Rolfe (1980) reported the results of a very careful, statistically sound comparison of loblolly and shortleaf pine plantations at various spacings on soil properties over a period of 25 yr. Results showed no effect of spacing, but significant differences between species: mineral soil organic matter was higher but 0 horizon weight was lower in the shortleaf pine than in the loblolly pine stand after 25 yr. Lane (1989) reported no differences in soil C after conversion of native hardwoods to loblolly pine in South Carolina. Alban (1982) compared soil properties in adjacent stands of trembling aspen (Populus tremuloides), white spruce (Picea glauca), jack pine (Pinus banksiana), and red pine (P. resinosa) at two sites in northern Minnesota. There were no differences in total forest floor weight among the stands at either site, but the aspen soil had significantly lower surface soil organic matter (10 to 40%) than the other species at both sites. One study of peripheral interest was that of Amendinger (1990) which indicated a large (>50%) loss of soil C with the invasion of jack pine in prairie during the Holocene inferred from a chronosequence study.

Feger et al (1990) reported the nutrient budgets of two contrasting watersheds in Germany which are relevent to the subject of species effects on soil C change. No soil C or N data were presented to document the actual decline in soil C, N, and S contents, and thus the study is not summarized in Table 5; however, some of the results are worth summarizing here. The sites were: Schluchsee, which has granitic bedrock and within which Norway spruce (Picea abies) are experiencing Mg deficiency, and Villingen, which has sandstone bedrock and within which Scots pine (Pinus sylvestris) and silver fir

Table 5. Effects of species change on soil C.

Location	Treatments	Results	Reference
Australia (Pinus radiata, Eucalyptus)	Radiata pine vs Eucalyptus	Soil C was greater (by 45% in surface and 27% in subsurface horizons) beneath pines in one site, no difference in another site.	Turner and Kelly 1985
Australia (P. radiata, Eucalyptus)	Radiata pine vs Eucalyptus	Pine had greater soil C in low fertility site, lower soil C in high fertility site.	Turner and Lambert 1988
Illinois (P. echintata, P. taeda)	Loblolly vs shortleaf pine plantations on former agricultural land	Greater soil C (20%) but lower O horizon in shortleaf plantations at age 25. No effect of spacing.	Gilmore and Rolfe 1980
Minnesota (P. banksiana)	Chronosequence of prairiet o jack pine	Large loss (>50%) inferred in jack pine invasion during the Holocene	Almendinger 1990
Clemson, SC (P. taeda)	Conversion of hardwood to loblolly pine	No change after 23 yr	Lane 1989
Minnesota (Pinus resinosa, P. banksiana, Picea glauca, Populus tremuloides)	Comparison of four species at 40 yr of age	Significantly less soil C under aspen (10-40%) than other species	Alban 1982

(Abies alba) are experiencing K deficiency. Of interest to this review are high rates of N and S leaching from the Schlucsee watershed, an effect attributable to the mineralization of organic matter left in subsoils from a deeper-rooted beech stand (Fagus sylvatica) which occupied the site 150 yr previously.

3.6 REFORESTATION AND SUCCESSION

Examining the changes in soil C during reforestation and succession is one way of gaining some insight into the long-term effects of harvesting, cultivation, etc., on soil C reserves (Table 6). In cases where former agricultural land is reverted to forest or where newly developing soil undergoes afforestation, soil C usually increases substantially.

In a study involving resampling of soils over time, Johnson et al (1988) noted either increases (30 to 100%) or no significant change in surface soil (0 to 15 cm) C over an 11-yr period in aggrading forests growing on former agricultural land on Walker Branch Watershed, Tennessee. Jenkinson (1970, 1991) reported the results of the Rothamsted studies of organic matter and nutrient changes in soils left uncultivated since the early 1880's. One site (Broadbalk) was on a calcareous soil that had been limed sometime during the 18th or early 19th century, the effects of which were still evident in the pH of samples taken in 1964 to 1965. The other site (Geescroft) received N and P fertilizers but no lime and consequently experienced significant acidification (pH 7.1 to 4.5) from 1883 to 1965. Differences in acidification were thought to have resulted in substantial differences in soil organic C, N, S, and P, all of which were greater at Broadbalk. Soil organic C in Broadbalk increased by 80% over the 83-yr period, whereas Geescroft increased by only half as much (Jenkinson 1970). Rates of N, S, and P accumulation were also considerably greater at Broadbalk than Geescroft. Of special interest was the finding that the rates of organic N accumulation (65 and 23 kg N ha^{-1} yr^{-1}) were greater than could be accounted for by either atmospheric deposition or N fixation by legumes.

Chronosequence studies have also shown significant soil C accumulation when former agricultural land is reforested or afforested. Wilde (1964) examined soil organic matter in 100 red pine (Pinus resinosa) plots of varying age (from 10 50 yr) planted on former agricultural land in Wisconsin. He found a linear increase in soil organic matter in the top 15 cm of soil with stand age, with the overall increase being 300 to 400% over 40 yr. Lugo et al (1986) assessed the affects of conversion of former agricultural land to either forest or pasture in Puerto Rico. They were motivated to test some of the assumptions used in global climate models that the top 1 m of soil loses 65% of its C after deforestation, and that it can return to within

Table 6. Effects of reforestation and succession on soil C.

Location	Treatments	Results	Reference
Wisconsin (Pinus banksiana)	100 plantations on old fields	Linear increase (+300 to 400%) in soil C in top 15 cm up through age 50	Wilde 1964
Virgnina (P. taeda, P. virginiana)	Old field chronosequence	35% increase in soil C over 50 yr	Schiffman and Johnson 1990
Puerto Rico (Subtropical wet and moist forests)	Coffee shade plantations vs secondary forest	50% greater soil C in secondary forest	Weaver et al 1987
Puerto Rico (Subtropical forests)	Conversion of agricultural land to forest or pasture	Approximate doubling of soil C within 50 yr, to within 90% of mature forest.	Lugo et al 1986
Florida (P. eliottii)	Chronosequence after forest harvest	Initially high A horizon soil C due to bedding of slash decreases by 50% to pre-harvest levels by age 5. No trend from ages 5 to 35.	Gholz and Fisher 1982
Rothamsted, UK (Mixed hardwoods)	Agricultural land reverted to forest	Approximate doubling of soil C over 83 years	Jenkinson 1970, 1991
Hubbard Brook, NH (Northern hardwood)	Old field chrono-sequence	Decrease (-20%) in Ap over 75 years. Increase in O horizon was greater than decrease in Ap.	Hamburg 1984
Oregon (Tsuga mertensiana)	Mt. hemlock waves	Decrease in forest floor in regrowth, no change in soil C	Boone et al 1988
Hawaii (Metrosideros collina ssp. polymorpha)	ohi'a forest on ash and lava flow	380 kg ha^{-1} yr^{-1} accumulation over first 191 yr; slower thereafter up to 4000 yr	Vitousek et al 1983

Tennessee (Mixed deciduous)	11-year interval sampling	Either no change or increases in soil C (20-100%)	Johnson et al 1988
Six Rivers, CA (Mixed conifer, Sequoia sempervirens)	Chronosequences following clearcutting	No change in fir after 25 yr; slight decrease (25%) in redwood until age 25, then increase Likely logging residue effect.	Durgin 1980

75% of its original value within 50 yr of abandonment of agriculture. They evaluated the effects of abandonment of agriculture in several life zones (subtropical wet, dry, and moist forest) through resampling of specific sites through time and chronosequence studies. They found that recovery of soil C was much more rapid than generally assumed in models: for instance, chronosequence studies indicated that abandoned agricultural soils in the wet and moist forest life zones regained 90% of the soil C in mature forests within 50 yr, and in the dry zone, recovery of soil C to levels in mature forests occurred within 30 yr.

Schiffman and Johnson (1990) compared C contents of two loblolly pine chronosequences, one growing on a former agricultural field, and one on a site converted from naturally-regenerated Virginia pine (Pinus virginiana). There was a large increase in ecosystem C content (235%), mostly due to phytomass in the old field chronosequence but only a 24% gain in the natural forest conversion chronosequence. Similarly, there was a large increase in soil C (57%) in the old field chronosequence and no significant change in the forest conversion chronosequence. The authors drew two important conclusions as to the effects of reforestation in the southeastern U.S.: 1) there were "negligible oxidative losses of carbon from soils after harvest and site preparation" of natural forests (p. 69), and 2) "the conversion of natural forests to plantations is no substitute for the farm to forest conversion" in terms of C storage. The latter is of significance, in view of the marked reductions in the rate of old field reforestation in this region.

An exception to the general pattern of increased soil C after reforestation of formerly cultivated soils is the study by Hamburg (1984) at Hubbard Brook, NH. In this case, Ap horizon soil C decreased over the 75-yr chronosequence. Even in this case, however, increases in 0 horizon C more than offset the decreases in Ap horizon C.

In cases where reforestation and succession follow previous forests, there is no clear pattern. As noted above, Schiffman and Johnson (1990) found negligible effects of forest conversion from native Virginia pine to loblolly pine. Boone et al (1988) found no change in soil C but a decrease in 0 horizon C in regrowth following hemlock waves in Oregon. Durgin (1980) found no changes in fir forests 25 yr after clearcutting and slight decreases followed by increases in redwood forests following clearcutting in California. In a chronosequence study in slash pine (Pinus elliottii), Gholz and Fisher (1982) found that the A horizon of a 2-yr-old stand contained approximately twice as much soil C as the other stands (up to age 34) in the chronosequence), which was attributed to bedded slash. Assuming that the chronsequence truly represented trends with time, the effect of slash bedding was very short-lived: soil C decreased by 50% to approximately pre-harvest levels by age 5.

3.7 NITROGEN FIXATION AND FERTILIZATION

For the purposes of this review, the effects of N-fixing species and fertilization on soil C were combined into one category (Table 7). For the most part, the presence of N-fixers caused substantial (20 to 100%) increases in soil C and N (Table 7). The one exception to this general rule was the study by Paschke et al (1989) in Illinois, which evaluated the effects of black alder (Alnus glutinosa) and autumn olive (Elaegnus umbellata) interplantings with black walnut (Juglans nigra). In this case, interplanting with both alder and autumn olive resulted in significantly greater mineral N levels and N mineralization rates than in walnut alone, but there were no increases in either soil total C or N with interplanting after 18 yr. Indeed, there was a clear and significant trend toward lower soil C and N in the autumn olive interplanted plantations than in walnut only plantations. Reasons for this were not known.

Another seeming exception to this general rule was the Cascade Head site in Oregon, where there was only an 11% difference in soil C between red alder (Alnus rubra) and Douglas-fir (Pseudotsuga menziesii) soils. In this case, however, the Douglas-fir soil was quite high in both C and N, and the 11% difference was actually about equal in magnitude to larger percentage increases at other sites (Binkley and Sollins 1990).

Fertilization generally caused an increase in soil C, as one would expect given its expected effect upon primary productivity. However, the increases in soil C with fertilization were generally not as large as those due to the presence of N fixers. Nohrstedt et al (1989) evaluated soil C and microbial activity in two sites in Sweden: Kroksbo, which was treated with ammonium nitrate and urea at 150 and 600 kg N ha^{-1} 11 yr previously, and Nissafors, which was treated with 150 kg N ha^{-1} as ammonium nitrate at both 8-yr and 1 yr previously (for a total of 300 kg N ha^{-1}). They found an increase of 16 to 25% in litter plus soil C in the Kroksbo site, and an increase of 10% overall in the Nissafors site. The effect was more pronounced at higher fertilization levels and more pronounced with ammonium nitrate than with urea. Interestingly, they could not account for the increased C with increased litterfall, and attribute the effect to reduced microbial activity per unit organic C.

Van Cleve and Moore (1978) noted increases in soil C of 13 to 17% with N (ammonium nitrate) and P (triple super P) fertilization of aspen sites in central Alaska. Turner and Lambert (1986) noted up to 22% increase in soil C 30 yr after a single superphosphate fertilization in a P-deficient Radiata pine plantation in New South Wales, Australia. In contrast, McCarthy (1983) found only a slight (5%) increase in soil C in slash pine plantations in Florida 20 yr after P fertilization. Gilmore and Boggess (1963) and Gilmore (1977, 1980) reported on studies

Table 7. Effects of nitrogen fixation and fertilization on soil C.

Location	Treatments	Results	Reference
British Columbia, Washington (Pseudotsuga menziesii, Alnus rubra)	N fixation	Increases by 30-100%	Binkley 1983
Wind River and Cascade Head, OR (P. menziesii A. rubra)	N fixation	36% increase (+28,020 kg ha^{-1}, p=90%) at Wind River, non-significant 11% increase of about the same absolute magnitude (+25,020 kg ha^{-1}) at Cascade Head	Binkley and Sollins 1990
Oregon (P. menziesii, Ceanothus spp.)	N fixation	40 to 60% increase with Ceanothus	Binkley et al 1982
Thompson, WA (P. Menziesii, A. rubra)	N fixation	50% more C in red alder soil	Brozek 1990
Wind River, OR (P. menziesii, A. rubra)	Interplanting with N fixers	Greater in surface soils in interplanting vs fir alone (+30-40%)	Tarrant and Miller 1963
Illinois (Juglans nigra, Alnus glutinosa, Elaeagnus umbellata)	Interplanting with N fixers	Increase (+22%, , not significant) with Alnus ; decrease (-15%, not significant) with Elaeagnus	Paschke et al 1989
Illinois (Platanus occidentalis, Fraxinus pennsylvanica, Liriodendron tulipifera)	Plantations on agricultural land previously treated with manure, crop residue, rock phosphate, and lime	Previously limed plots were 20-30% higher (p=95%) throughout the study. Manuring added increase, and yellow-poplar had higher C, also	Gilmore 1977

Illinois (<u>Pinus taeda</u>, <u>P. strobus</u>, <u>P. resinosa</u>, <u>P. echinata</u>)	Plantations on agricultural land previously treated with manure, crop residue, rock phosphate, and lime	Soil C was 2x greater in limed plots in 1955 but by 1978, differed by only 10-20% (p=95%). Soil C in unlimed plots increased to near limed plot levels.	Gilmore 1980
Florida (<u>Pinus elliottii</u>)	P fertilization	Slight increase (5%) with highest application (157-314 kg ha^{-1}. Very large increase in forest floor. (No statistics)	McCarthy 1983
Sweden (<u>Pinus sylvestris</u>)	Urea and ammonium nitrate at 150 and 600 kg N ha^{-1}	10-26% greater C in fertilized plots most pronounced at higher fertilizer levels and with ammonium nitrate. Effect due to reduced microbial activity rather than greater litterfall. (Not significant at 95% level)	Nohrstedt et al 1989
New Zealand (<u>P. radiata</u>)	N,P,K,S,Ca, and Mg fertilizer and lupines on sand dunes	9% increase with lupine (p=95%), 6% increase with fertilization (not sign.) 17% increase with both (not sign.)	Baker et al 1986
Australia (<u>P. radiata</u>)	Superphosphate	Up to 22% increase with 100 kg P ha^{-1}.	Turner and Lambert 1986
Alaska (<u>Populus tremuloides</u>)	Ammonium nitrate (777 kg ha^{-1}), triple super P (385 kg ha^{-1}), KCl (111 kg ha^{-1}.as K) over a 6-yr period	Increase in surface soil with N (+30%, p=95%) and P (+34%, p=95%)	Van Cleve and Moore 1978

where various tree species (both pines and hardwoods) were planted on agricultural soils previously treated with manure, crop residue, P (rock phosphate) and limestone, both singly and in combination. In the hardwood plantations, previosusly limed plots had significantly greater (20 to 30%) soil organic matter at the start of the study, and the effect carried through the 18th yr. In the pine plantations (P. taeda, P. echinata, P. resinosa, and P. strobus), previously limed soils had twice as much organic matter (OM) initially (in 1955). Soil OM increased in both limed and unlimed plots, but at a greater rate in the unlimed plots, so that at age 24, the limed plots were only 20 to 25% higher in soil OM.

Baker et al (1986) compared the effects of mixed fertilizer (960, 410, 410, 140, 200, and 290 kg ha^{-1} of N, P, K, S, Ca, and Mg, respectively), lupine (Lupinus arboreus), and lupine plus fertilizer on planted radiata pine on sand dune sites in New Zealand. They documented a statistically significant effect of fertilization on soil C (115% in the top 5 cm). Lupine and lupine plus fertilizer also caused increases (47 and 89%, respectively), but these were not statistically significant. To a 1 m soil depth, the effects of treatments were somewhat different, however: only the lupine treatment was significantly different from control (9% greater), although fertilizer and lupine plus fertilizer treatments alone also resulted in increases (6 and 17% greater, respectively).

4. Conclusions

Despite the numerous uncertainties and caveats noted in Section 2, the results of this literature review reveal some reasonably consistent results and trends in soil C under various forest management scenarios. It has long been established and remains clear that cultivation leads to substantial decreases in soil C in all but the most C-poor soils (Figure 2; Mann 1985, 1986; Schlesinger 1986; Detwiler 1986). However, the assumption that soil C decreases on the order of 30 to 40% following forest harvesting (e.g., Houghton et al 1983; Musselman and Fox 1991) is not supported by the literature reviewed here. Rather, it appears as if losses of soil C after harvesting and reforestation are negligible in most cases. The effects of harvesting, site preparation, and burning on soil C (not including litter) are summarized in Figure 3a and b. In Figure 3a, only statistically significant results are reported whereas in Figure 3b, all results are reported.

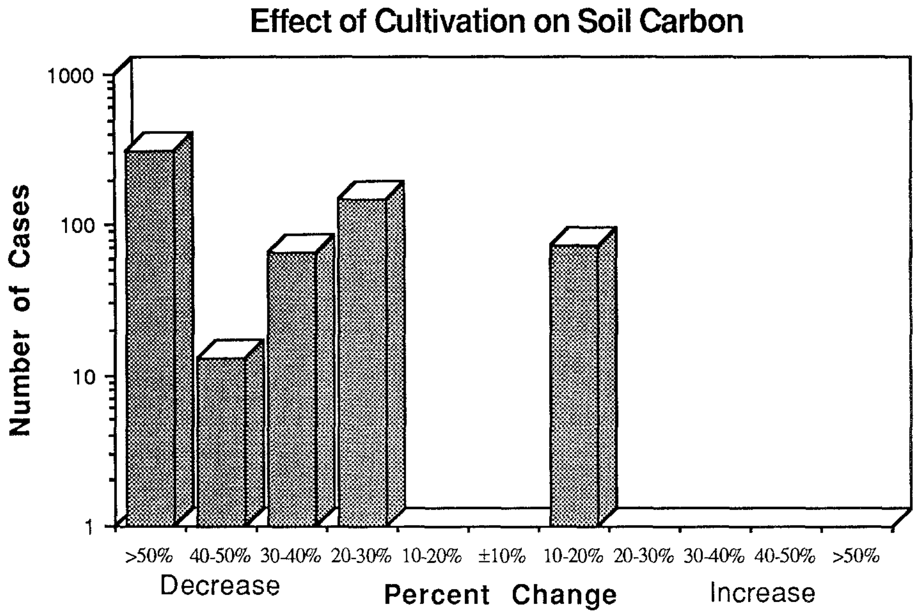

Figure 2. Frequency distribution of the percentage change in soil C with cultivation (see Table 2 for data sources).

Regardless of whether only statistically significant differences or overall trends are considered, the majority of studies reviewed here indicate little or no change in soil C (i.e., $\pm$ 10%) following harvesting and reforestation. The exceptions to this are primarily in the tropics, where recovery to original levels after reforestation is apparently quite rapid, and in cases where harvesting is followed by intense broadcast burning (e.g., Sands 1983). However, there are also instances where soil C increased after harvesting, probably due to the additions of slash, increased decomposition rates, and incorporation of organic matter into the mineral soil (e.g., Gholz and Fisher 1982; Henricksen et al 1989).

It is important to recognize that cultivation for crops differs substantially from harvesting and site preparation in new forest plantations. Crop cultivation typically involves much more severe and prolonged disturbance than harvesting, even with intensive site preparation. Crop cultivation also very likely leads to long-term increases in soil temperature, whereas soil temperatures are likely return to near pre-harvest levels rapidly after the development of a new forest canopy. Thus, it is not at all surprising that soil C losses following harvesting and reforestation are substantially less than with harvesting followed by cultivation, and these differences must be taken

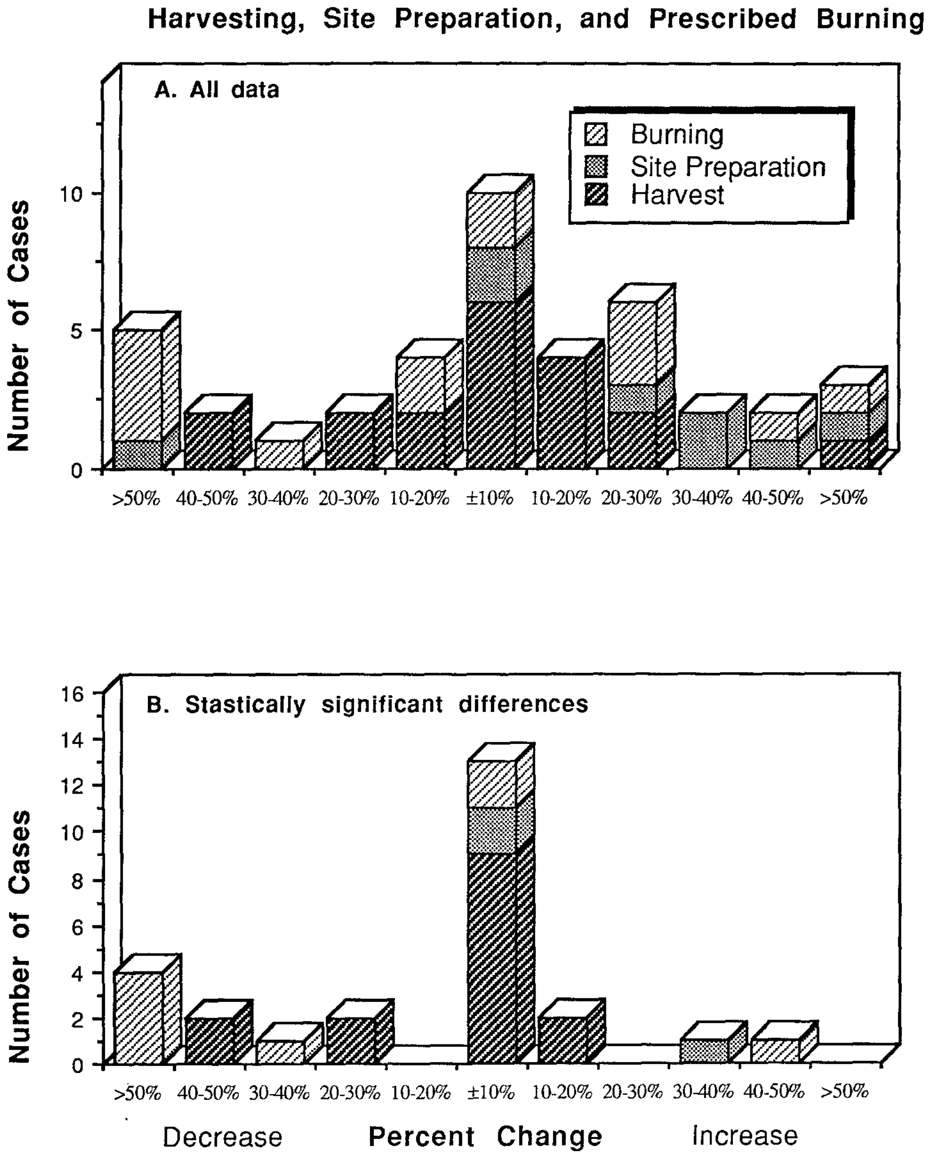

Figure 3. Frequency distribution of the percentage change in soil C with forest harvesting, site preparation, and burning. A. Statistically significant differences only shown (non-significant differences included in the ± 10% category), B. All differences shown. (See Tables 1,3, and 4 for data sources).

into account when evaluating the effects of forest harvesting in general on global C balances. It is likely true that harvesting and cultivation result in large changes in soil C on the order of 30 to 50% over a period of several decades. However, there is nothing in the literature to suggest that such changes occur when harvesting is followed by forest replanting.

It is clear that the effect of fire upon soil C is a function of fire intensity. A light or moderate burn causes a mobilization of nutrients, and may be beneficial to the growth of the subsequent forest. Figure 4 shows that the effects of regular prescribed fire on soil C is heavily

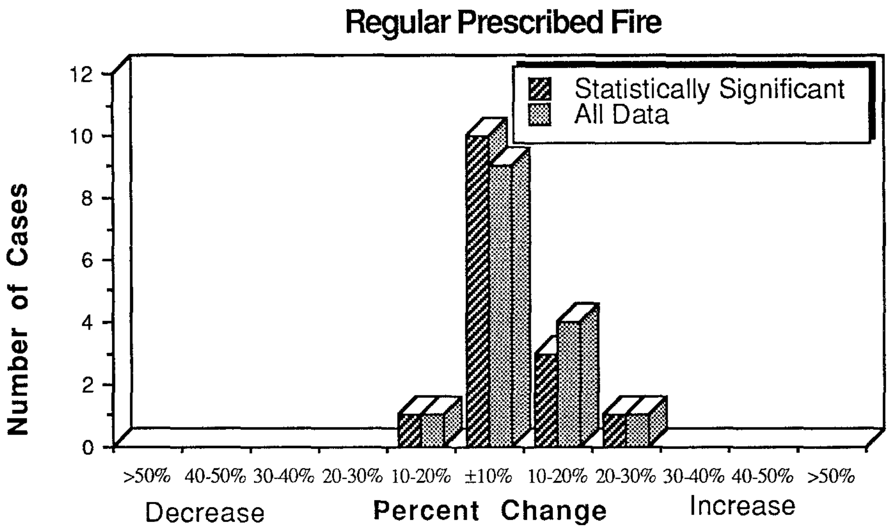

Figure 4. Frequency distribution of the percentage change in soil C with regular prescribed fire. S=Statistically significant differences only shown (non-significant differences included in the ± 10% category), A=All differences shown. (See Table 6 for data sources).

weighted toward the center (negligible effect) but somewhat skewed right, indicating a positive effect. An intense burn, on the other hand, may deplete the soil of volatile nutrients (including N, S and P; Raison et al 1985), causing a long-term decrease in forest productivity and C sequestration.

There are clearly opportunities for increasing soil fertility and the fixation of C in forest ecosystems through the management of forest nutrition: there is a marked, clear trend toward greater soil C with the introduction of N-fixers as well as with fertilization (Figure 5). The benefits of this must be weighed against the cost of fertilization or the cost of allowing N-fixing species of low economic value to inhabit the sites in question.

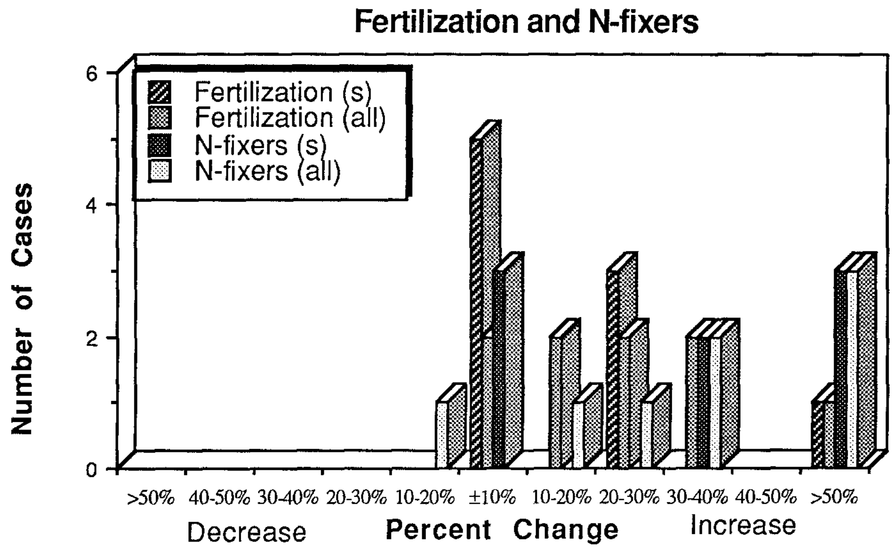

Figure 5. Frequency distribution of the percentage change in soil C with N fixers and fertilization S=Statistically significant differences only shown (non-significant differences included in the ± 10% category), A=All differences shown. (See Table 7 for data sources).

There are two possible reasons for the increase in soil C following N fixation and fertilization: 1) increased productivity and, therefore, increased organic matter input to soils, and 2) stabilization of soil organic matter. In the case of N, non-biological condensation reactions of phenols with ammonium are important in the production of humus (Mortland and Wolcott, 1965; Paul and Clark 1989). These reactions are enhanced by high pH (because NH_3 is the reactive form of N) and high NH_3 and/or NH_4^+ concentrations. Both of these conditions occur following urea fertilization, which is known to cause non-biological NH_4^+ fixation (Foster et al 1985). In the case of Ca and other polyvalent cations, cation bridging of organic colloids causes condensation and stabilization of organic matter (Oades 1988). Oades (1988) suggests that the well-documented positive relationship between soil clay and organic matter content may actually be the result of greater polyvalent cation availability (either Ca or Al) in clay rich soils. Because Ca is rarely limiting to tree growth, the positive effects of liming on soil C noted by Gilmore (1977, 1980) and Jenkinson (1970, 1991) are likely due to these reactions rather than a direct effect upon plant primary productivity.

5. Research Needs

As noted in the Objectives and Methods section, there are numerous inconsistencies in the way data was collected and summarized in the studies reviewed here. This is certainly not meant as a criticism of these studies, each of which was designed to test a specific hypothesis or answer a specific question. However, there is a clear need for a coordinated, regional study on the effects of forest management on soil C dynamics such as has been done for nutrient effects (e.g., Mann et al 1988) and such as that proposed by Powers et al (1990). Such a study should control for both management practices (e.g., degree of residue removed, burning, bedding, etc.) and establish sampling protocols that eliminate the current uncertainties arising from unknown effects of spatial and temporal variation among study sites.

In addition to (or in conjunction with) a coordinated regional study, more research is needed on the processes controlling soil C accumulation and loss. What are the roles of temperature versus moisture on decomposition? What are the effects of extremes versus changes in mean values of temperature and moisture? What role do nutrients play in stabilization or loss of soil organic matter? Such process studies should include not only changes in litter decomposition, which has been extensively studied, but also the incorporation of litter into soil organic matter and, ultimately, humus. Investigations of soil C fractions, even on existing study sites, may be a meaningful first step in obtaining insight into important processes.

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