The Potential of U.S. FOREST SOILS to Sequester Carbon and Mitigate the Greenhouse Effect

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CHAPTER 14

Soil Carbon Sequestration and Forest Management: Challenges and Opportunities

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CONTENTS

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INTRODUCTION

The subject of the effects of forest management activities on soil carbon is a difficult one to address, but ongoing discussions of carbon sequestration as an emissions offset and the emergence of carbon-credit-trading systems necessitate that we broaden and deepen our understanding of the response of forest-soil carbon pools to forest management. There have been several reviews of the literature, but hard-and-fast conclusions are still difficult to draw, since many of the studies reviewed were not designed specifically to address management effects on soil carbon, were conducted on a short timescale, and differ in the methodology employed.

Johnson's (1992) oft-cited review examined papers dealing with the effects of harvesting, cultivation, site preparation, burning, species conversion (and species comparisons), reforestation/succession, and fertilization/nitrogen fixation. Johnson and Curtis (2001) have since expanded that review, including more papers and a meta-analysis.

This review focuses on the effects of forest management actions, mainly silvicultural treatments, on soil carbon. Carbon gain due to afforestation and carbon loss as a result of conversion to agriculture are not addressed here, and studies involving only the forest floor (excluding mineral soil) are not discussed. In addition, most examples are drawn from U.S. forests, though research from other countries is reported when U.S. examples are few in number; for example, many fire studies have been conducted in the Mediterranean area. The papers included in this review are drawn from multiple searches of forestry, agriculture, and soils document databases employing a wide variety of search terms and search services, and they are intended to provide a comprehensive review of available literature without unnecessarily duplicating the work of Johnson (1992) or Johnson and Curtis (2001). The purpose of this review is not to cover the same ground as previous reviews of this subject but to highlight those findings, report on additional studies not covered in existing reviews, underscore the difficulties in comparing soil-carbon studies, and raise some issues that are not often addressed.

CHALLENGES IN CONDUCTING FOREST-SOIL CARBON STUDIES

Before discussing the findings in the literature, it is important to note some caveats. It is only recently that studies have been designed specifically to examine the effects of forest management activities on forest-soil carbon. A recent review by Heath and Smith (2000) points out that many studies on which current conclusions are based were not designed to detect changes in soil carbon. These studies were commonly designed to investigate the possible depletion of site nutrient capital as a result of forest management activities, and carbon measurements were later overlain on the existing design. Since soils are spatially variable, these studies may lack sufficient replication to detect treatment effects, making the findings of limited usefulness. That is, treatment effects that are not significantly different from controls may simply reflect a study design with a sample size that was too small to detect differences statistically. Another common problem is the lack of data on initial conditions. While it may be known that a stand was clear-cut 50 years previously, no soils data were gathered at the time, and current carbon measurements are tested against a reference forest of similar characteristics and age. The difficulty is obvious: No information exists as to the condition of the forests at the time of the management action, so that present differences may be the result of differing "initial conditions" or of some other factor. Many studies fall into this category, and while they may be informative, it is difficult to conclude with certainty that any gain or loss of carbon is attributable to the management action.

A persistent problem of previous studies is the lack of a standardized sampling protocol: Some studies include the entire forest floor (or a portion of it) in the first depth increment, while others begin the sample at the mineral soil. Since the carbon concentrations and dynamics of the forest floor and the mineral soil are quite different, a clear distinction should be drawn between the two.

Many studies have shown a decrease in carbon content in the upper 5 or 10 cm but an unchanged carbon pool for the entire depth sampled. Studies that only sample the upper 10 or 20 cm may show a decrease or increase in carbon content when, in fact, a redistribution of carbon occurred with the total pool size remaining unchanged. This problem is especially difficult to overcome, since sampling to greater depth in rocky forest soils is often not possible without great effort, and so is not feasible on a routine basis. Depth increments used for sampling and reporting vary widely, with some investigators sampling by soil horizon and others employing predetermined depth increments. These increments also vary: The literature contains studies with initial increments that range from 2.5 cm up to 30 cm, further complicating comparisons across studies. While it may be impractical for all investigators to implement a standard sampling protocol, every effort should be made to separate forest floor from mineral soil and to sample to the greatest depth possible under the circumstances. This will facilitate comparisons between studies as well as providing a more accurate picture of soil-carbon dynamics.

Methods of soil analysis also differ: While most investigators use equipment that employs the modified Dumas method (such as a Leco C analyzer or Carlo-Erba CHN analyzer), some still utilize the Walkley-Black procedure (wet combustion) or the loss-on-ignition method, with a conversion from organic matter to carbon. (This conversion factor can be determined empirically, but in many cases a fixed conversion factor is used.) Studies conducted outside the United States employ some additional variations on wet-combustion methods. Not all of these methods produce good agreement in all soils (wet combustion can seriously over- or underestimate soil organic carbon relative to dry combustion), which further complicates comparisons between studies or points in time (Nelson and Sommers, 1982). Currently, dry combustion is recommended as the best method for the analysis of total C in soil and litter (Sollins et al., 1999) and should be used whenever possible. When conducting a long-term study with repeated measurements, investigators should archive sufficient soil so that reanalysis is possible if methods change substantially over the course of the study, or for the use of other investigators conducting follow-up studies. Archived soils can be a major key for reinterpretation of long-term studies designed for understanding soil-carbon dynamics and their response to management or other factors.

Perhaps the greatest difficulty encountered with soil-carbon studies is the lack of bulk-density measurements. More studies are now reporting both concentration and content, but often carbon concentration is the only variable reported. Although data on the concentration of carbon are useful, they provide only a part of the necessary information. If we are trying to assess the effects of forest management practices on soil carbon with an eye to constructing a carbon budget, then the variable of interest is the size of the carbon pool, not the concentration of carbon. To assess the magnitude of the soil pool and changes in carbon storage in soils, bulk density must be measured. A related issue is that scenario analyses and projections often assume that there will be no changes in site productivity after harvest and regeneration. Increases in bulk density have been shown to decrease productivity. The effects vary by species; some are tolerant, while others show a decrease in height and/or diameter growth (Omi, 1986). Seedling establishment may also be affected. In summary, investigators should hesitate to draw firm conclusions from studies reporting only concentration data, or where concentration data were converted to content using a fixed value for bulk density, until comprehensive studies show that the conversion factors are adequate.

A separate but related issue arises when sampling in disturbed areas. In sites under intensive management, considerable ground disturbance can occur as a result of practices such as shearing, bedding, chopping, or disking. All of these operations will affect bulk density as well as mixing surface organic material into the mineral soil. Decisions about where to sample can be quite difficult in these situations; some investigators employ a systematic grid, while many strive to avoid disturbed areas. Rarely is a photographic record of the site condition included with the data, and estimates of the percentage of the total study area disturbed (as well as the degree of disturbance) are generally not reported. In cases such as these, a careful description of site conditions should be included, as well as a detailed description of how the sampling was conducted. Compositing of samples from disturbed and undisturbed areas should be avoided; in these cases a stratified sampling design will make interpretation of the results more straightforward.

While the challenges outlined above may seem daunting, it does not mean that past soil-carbon studies are without value. Each study imparts information worth knowing, but because of the factors mentioned above, caution should be used when attempting to draw broad conclusions about the effects of forest management on soil carbon storage across varying forest types and management histories. We need to learn from these obstacles and design studies that are robust and permit comparisons with similar work. With that in mind, what is the current state of knowledge?

HARVESTING AND SITE PREPARATION

Keeping in mind the interpretation challenges discussed in the previous section, the most recent review (Johnson and Curtis, 2001) reached essentially the same findings as Johnson's previous (1992) work. With regard to harvest effects, 13 papers were included in the first review, 26 in the second. Harvesting was considered independently from site-preparation effects; whole-tree and sawlog-only harvesting were also examined. The meta-analysis of Johnson and Curtis (2001) showed no statistically significant harvesting effect on soil organic carbon (SOC), but it did show that sawlog harvest of coniferous species resulted in a significant increase in soil carbon in the A horizon. However, for the B horizon and the whole soil column, there were no significant effects of harvest type or time since harvest. Note that soil is highly variable, so that large sample sizes may be needed to pronounce statistical significance. Since Johnson and Curtis (2001) conducted a meta-analysis, they did not employ a traditional significance value to test for differences; rather, means were considered to be significantly different if the 95% confidence intervals were nonoverlapping. Results were considered to be significantly different from zero (no change in soil C) if the 95% confidence intervals did not overlap zero. Results not meeting this criterion were said to be not significant. The papers reviewed below, except for Johnson and Curtis (2001), generally use the common significance value of $P \leq 0.05$.

Northeastern United States

Many studies on harvest effects have been conducted in the Northeast, especially at the Hubbard Brook Experimental Forest. Snyder and Harter (1984) examined a chronosequence of stands in the White Mountain National Forest. Stands were matched with respect to vegetation, soil series, elevation, aspect, parent material, and physiographic position. Three even-aged stands were chosen: 3, 10, and 30 years after harvest. The 3- and 10-year stands resulted from an 8- to 12-ha clear-cut, the 30-year stand from a 3- to 4-ha patch cut. To represent preharvest conditions, a 93-year-old second-growth stand located near the 3-year site was used. Soils were sampled by horizon to a depth of 1 m. Organic carbon concentrations were not significantly different across stands in the chronosequence; no information was given on carbon content.

Several publications detail the results of a whole-tree harvest experiment at the Hubbard Brook Experimental Forest (Johnson, 1995; Johnson et al., 1995; Johnson et al., 1991; Huntington and Ryan, 1990). Sampling was conducted immediately prior to, 3 years after, and 8 years after whole-tree harvesting. Mineral-soil samples were taken at depths of 0 to 10 and 10 to 20 cm and from 20 cm to the C horizon. Bulk density three years after harvest had increased, up to 14% on disturbed sites, but this increase was not statistically significant. There were no statistically significant changes in the organic-matter pool for the whole soil column, although organic matter was redistributed between depth increments (Johnson et al., 1991). The 8-year postharvest results reported by Johnson (1995) indicate a significant decline in the mineral-soil C:N ratio after whole-tree harvest. The carbon pool in the mineral soil increased by 10 Mg/ha 3 years after harvest, then declined (from precut values) by 12 Mg/ha 8 years after harvest, but these changes were not statistically significant.

Johnson also stratified the results spatially into the spruce-fir, high-hardwood, and low-hardwood zones. When carbon pools were considered by zone, differences were detectable: the low-hardwood zone showed a significant decline in mineral soil carbon 8 years after the clear-cut (20 Mg/ha); carbon pools in the spruce-fir zone were unchanged; and in the high hardwood zone, mineral-soil carbon content also declined, but this was not statistically significant.

In West Virginia, a chronosequence of stands ranging in age from 0.5 to 23 years after cutting was examined (Mattson and Smith, 1993). Each stand was paired with an adjacent uncut stand for purposes of comparison. While cutting types and slash treatments varied among the 15 stands, in each case forest-floor disturbance was minimal, and no mechanical site preparation was conducted. Mineral soil was sampled to a depth of 10 cm, and CO_2 efflux was measured six times during a 12-week period in the summer of 1987. There were no statistically significant cutting effects on bulk density, organic matter content of the 0- to 10-cm soil layer, or CO_2 efflux. In addition, there was no significant trend of mineral-soil carbon content with respect to time since cutting. A study conducted in the Daniel Boone National Forest in Kentucky (Morris and Boerner, 1998) compared managed and unmanaged plots on two sites of differing soil nutrient status. The managed plots had been heavily thinned (70 to 90% biomass removal) in 1958–1960, while the control plots were unmanaged and similar in composition to the thinned plots prior to treatment. The higher-quality site had significantly higher pH, NH_4, Ca, Mg, K, and P, and lower Al than the lower-quality site. In both forests, pH, extractable NO_3, Ca, and the Ca:Al ratio were significantly higher in managed than unmanaged plots, while the concentration of organic carbon was significantly higher in the managed plots at the high-quality site but similar between managed and unmanaged plots at the lower-quality site. This interaction between site characteristics and treatment (also seen in Johnson, 1995) is an indication that forest soils most likely do not respond uniformly to management activities, and many factors need to be considered when attempting to generalize about the effects of management on forest-soil carbon stocks.

Lake States

Two reviews of soil-carbon changes in the Lake States are available (Rollinger and Strong, 1995; Rollinger et al., 1998), and both generally conclude that there are no significant harvest or species-conversion effects on soil carbon storage. Harvest effects were sometimes seen at one depth but were not significant, and changes over the entire soil profile were not significant. Stand conversion from second-growth hardwoods to red pine caused a change in the carbon distribution with depth, but the pool size remained the same. Strong (1997) measured carbon storage across a range of harvesting intensities: heavy, medium, and light individual tree selection; a diameter-limit cut; and a control plot. Treatments were applied in 1952, but no soils data were taken at the time. Plots were measured in 1992; the diameter-limit treatment did contain significantly less soil carbon than the other treatments, but only in the 3- to 10-cm depth increment. While total pool (0 to 40 cm) sizes were not significantly different across cutting intensities, there was a significant trend of decreasing soil carbon with increasing harvest intensity, as measured by residual basal area at time of treatment. Although not a statistically significant difference, plots subjected to light and moderate cutting had higher stand-level carbon stocks.

Alban and Perala (1992) conducted a two-part investigation, looking at harvest effects using a chronosequence of 0 to 80 years and a pre- and postharvest study. Soils were sampled in 0- to 25-cm and 25- to 50-cm depths, but both litter and coarse woody debris were included in the soil component. Harvesting was conducted when the soil was frozen, and no ground disturbance resulted. No significant differences were found in soil carbon across the chronosequence or at 0, 5, and 7 years after harvesting. McLaughlin et al. (1996) investigated the effects of two harvest treatments in a Michigan spruce swamp: whole-tree harvest and whole-tree harvest plus site-preparation bedding. Five years after harvest, there were no significant treatment effects on SOC concentrations, but the SOC content in the surface horizon was significantly higher in the bedded treatment vs. the control and harvest-only treatments. When all mineral horizons were combined, the SOC content in the upper 50 cm was similar for the control and bedded plots, while the harvest-only plots contained approximately 20% less SOC.

Southeastern United States

Similar studies have also been conducted in the Southeast, and the results also indicate minor changes in soil carbon stocks as a result of harvesting. Schiffman and Johnson (1989) assessed a chronosequence of 11 loblolly pine plantations (1 to 26 years old) in the Virginia Piedmont. The stands were previously naturally regenerated pine that was clear-cut, then chopped and burned before replanting. Three 50- to 70-year-old naturally regenerated pine stands were used as reference forests. Soils were sampled from 0 to 10 and 10 to 33 cm, with additional samples to 1 m. There were no statistically significant differences in carbon content in surface or subsurface soils along the chronosequence. While care was taken to ensure that the stands were as closely matched as possible, the chronosequence was not repeated elsewhere. As with any chronosequence study, site effects cannot be ruled out.

At the Walker Branch watershed in Tennessee, two watersheds were clear-cut and the residue removed, two watersheds were clear-cut with sawlogs only removed, and the fifth watershed served as a reference (Edwards and Ross-Todd, 1983). No significant differences in SOC concentrations to a depth of 45 cm were detected, either before treatment or 5 months after harvest. Johnson and Todd (1998) elaborated on that work, reporting results from a resampling about 15 years later, using the same protocols and archived soils. No significant treatment effects on bulk density or carbon storage were detected, although carbon storage had increased significantly in the surface soils of all three treatments. It is important to note that the original soils were analyzed using the Walkley-Black method, while the later results used a dry-combustion method. Reanalysis of the archived samples revealed good agreement between the 1980 and 1995 nitrogen methods (Kjeldahl and CHN analyzer, respectively) but a significant bias in the carbon results, with the Walkley-Black method giving consistently higher carbon concentrations than the CHN analyzer. Since the nitrogen results agree, the authors feel that the difference is not due to changes during storage but, rather, to error in the Walkley-Black method. If archived soils from 1980 had not been available to reanalyze with modern methods, the significant increase in soil carbon in all treatments over time would not have been detected, since the 1980 values would have been artificially high relative to results from analysis by dry combustion. Such overestimation of carbon by wet-chemical methods could, in fact, lead to the spurious result of an overall decline in carbon over time, when compared with more recent samples analyzed by dry combustion.

A similar study was conducted at the Coweeta Hydrologic Laboratory in North Carolina (Knoepp and Swank, 1997). Again, five watersheds were used: two reference watersheds (undisturbed since the 1920s); a white pine watershed, planted in 1956; a mixed-hardwood watershed (subjected to whole-tree harvest); and another mixed-hardwood watershed with three communities: cove hardwoods, chestnut oak, and scarlet oak-pine (subjected to commercial sawlog harvest). Initial soil samples were taken in 1977 for the south-facing reference watershed, 1970 for the white pine and north-facing reference watersheds, 1979 for the whole-tree harvest stand, and 1975 for the commercial sawlog harvest site. The latter two watersheds were harvested after the initial samples were taken, and all five watersheds were sampled at the 0- to 10- and 10- to 30-cm depths in 1990. Carbon determinations were performed using the Walkley-Black method until 1983, when the dry-combustion method began to be used. In this case, good agreement was found between values obtained from the two methods. Unfortunately, only concentration data are reported, and the carbon data from the south-facing reference watershed (which was sampled annually from 1977 through 1994) show high interannual variability, increasing the difficulty of interpretation. Soil carbon concentrations were unchanged in the 0- to 10-cm layer but increased significantly in the 10- to 30-cm depth increment. There were no significant changes in carbon concentration at either depth in the whole-tree-harvest watershed, while concentrations in the sawlog-harvest watershed increased significantly in the 0- to 10-cm layer the first and second years after harvest (no differences were detected in the 10- to 30-cm layer). Carbon concentrations in the 0- to 10-cm layer of this treatment remained higher than pretreatment values 18 years after treatment, but only the first- and second-year postharvest values were significant.

Another Coweeta study was conducted on three south-facing hardwood watersheds. One watershed was left as a control, and the other two had all merchantable trees cut and removed by a cable-yarding system (Mattson and Swank, 1989). On one of these watersheds the unmerchantable stems were felled and left in place, while on the other all remaining woody material was removed by hand. No significant declines in soil carbon content were detected 5 or 8 years after cutting on the treated watersheds, and no residue treatment effects were evident.

Three treatments were applied to a forested wetland in Alabama (Aust and Lea, 1991): helicopter logging, rubber-tire skidder logging, and helicopter logging plus herbicide application. The stand was 70 years old prior to treatment, and measurements were made the first and second years after treatment. The sites did not differ in organic-matter content before harvesting. After harvest, soil organic-matter levels were significantly lower in logged areas relative to the uncut reference plots. While there was no significant difference between the helicopter and skidder treatments, the helicopter-logging-plus-herbicide plots contained significantly less soil organic matter. By two years after harvest, only the herbicide-treated plots contained significantly less organic matter, while the other treatments were not significantly different from the reference area.

Van Lear et al. (1995) measured soil carbon in loblolly pine stands in the South Carolina Piedmont. The land-use history is complex; the soils were badly eroded farmland planted to loblolly pine in 1939. The area was treated with low-intensity fire each year from 1977 to 1979, then clear-cut and left to regenerate naturally. An adjacent 55-year-old plantation served as a reference site. Soil carbon was measured at both the treated and reference sites at the time of harvest, and 1, 2, 3, and 13 years afterward, at depths of 0 to 10, 10 to 30, and 30 to 50 cm. Soil carbon concentration of soils in the harvested sites increased in the two years after harvest, then declined in the third year. By 13 years postharvest, carbon concentrations in the 0- to 10- and 10- to 30-cm depth increments were significantly higher in the soils of the harvested site; no carbon content information was provided.

Northwestern United States

Cole et al. (1995) investigated soil-carbon responses to a set of forest harvest and conversion experiments at the Cedar River Watershed in Washington. Adjacent red alder and Douglas-fir stands were harvested and replanted according to the following scheme: fir-to-fir, fir-to-alder, alder-to-alder, and alder-to-fir. Carbon was measured before harvest and 7 years after harvest and conversion, in depth increments of 0 to 7, 7 to 15, 15 to 30, and 30 to 45 cm. The fir-to-fir plot showed no change in soil carbon content 7 years after harvesting and regeneration, while replanting the fir site with alder resulted in an apparent carbon increase of 27% (difference not significant). Harvest and replanting of both alder plots resulted in a loss of soil carbon; the decline was significant for the alder-to-alder plots, with a reported loss of 27,000 kg C/ha over the 7-year period.

Canada

Several harvest studies have also been conducted in Canadian forests. One such experiment examined the effects of harvest and site preparation separately (Schmidt et al., 1996). A 100-year-old spruce-aspen forest was clear-cut in the fall of 1990, and site preparation was conducted 4 to 5 months later. Some study blocks were left unharvested to serve as reference plots. The following site preparation treatments were applied: no site prep (control), disk trencher, ripper plow, and blading. The experimental design was replicated at two locations. Soil sampling at the 0- to 7- and

20- to 27-cm depths was conducted 20 months after harvest in all sites, harvested and unharvested. No significant harvest effects on soil carbon concentrations were reported for either study location. All three mechanical site-preparation methods caused a significant reduction in carbon concentration in the 0- to 7-cm depth increment at one of the study locations; while declines were evident at the other site, only in the severely disturbed bladed plots was this decline statistically significant. At the 20- to 27-cm depth (reported for only one site), significant declines in carbon concentrations were observed for all three treatments, but only in the more-disturbed plots. Less-disturbed microsites did not show a significant decline.

Munson et al. (1993) examined the effects of clear-cutting combined with other silvicultural treatments; SOC was measured by the Walkley-Black method for the upper 10 cm of soil. The study was conducted in planted white pine and white spruce and was a factorial design combining the following treatments after clear-cutting: humus and debris intact or scarification, no fertilization or repeated NPK applications, and no competition control or repeated herbicide applications. White pine and white spruce were planted at 2 m × 2 m spacing. No significant effects on soil carbon concentration or soil C:N ratio were detected 4 years after the initial treatments. In Canada's Great Lakes-St. Lawrence forest region, Hendrickson et al. (1989) measured organic matter by loss-on-ignition at depths of 0 to 5, 5 to 10, and 10 to 20 cm 3 years after whole-tree and conventional harvests of a stand of red pine, white pine, and aspen and reported no significant changes in organic-matter concentration in either harvest treatment.

Pennock and van Kessel (1997) applied a chronosequence approach to study clear-cutting effects in Saskatchewan. A sequence of 80- to 100-year-old mixed-wood and previously mixed-wood clear-cut sites were used. Time since harvest was 1, 3, 9, 11, 15, and 19 years; a total of 17 sites across the region were studied. Total organic carbon was determined by dry combustion for depths of 0 to 15, 15 to 30, and 30 to 45 cm; the surface organic layer was included in the first depth increment due to the difficulty of separating surface organics from mineral soil in sites recently disturbed by harvesting and site-preparation activities. There were no significant differences in bulk density between harvested and mature sites. Clear-cut sites showed a significant increase in soil carbon content (relative to mature sites) in the first 5 years following harvest, but sites in the 6- to 20-year postharvest category had significantly lower soil carbon stocks than mature sites (a 23.5% average loss for the 0- to 45-cm depth range). This study indicates that short-term effects may differ substantially from long-term effects, and this factor should be considered when assessing management impacts on soil-carbon status.

Other Nations

An Australian study provides a different perspective, using both paired-plot and chronosequence approaches to study the effects of conversion of native forest to plantation forest (Turner and Lambert, 2000). Paired plots from a previously established study in fairly mature radiata pine plantations (20 to 50 years) and native *Eucalyptus* forest were examined for SOC changes. Data were available only for the 0- to 10-cm depth, but of the 18 pairs of sites compared, 17 had lower organic carbon concentrations in the plantation soils than in soils under native forest, and in many cases the pairs were replicated and differences were statistically significant, with the average decrease about 15% of the SOC concentration in the adjacent native forest plots. The pine and eucalyptus chronosequences were established in two locations; stands in the chronosequence were matched with respect to soil parent material and stand history. In the radiata pine chronosequence, the youngest (2 years old) stand showed a decline in SOC content in the 0- to 10-cm depth relative to adjacent undisturbed forest; older stands did not differ. When carbon in the 0- to 50-cm increment is considered, a slight decline in SOC content was observed throughout the entire chronosequence. The eucalyptus chronosequence, established on a former pasture, showed a small initial decline up to about 15 years post-establishment and then stabilization, while results for the 0- to 50-cm depth reveal a larger initial decline, with stabilization reached a few years later. These results from

Australia show the importance of monitoring deeper soils where possible, and the sharp contrast with most available U.S. and Canadian studies indicates that extrapolation of results from one location to another should be approached with caution.

Harvesting and Site Preparation Effects: Conclusions

Surveying available literature from a range of geographic regions (see Table 14.1 for a summary of most of the studies covered in this section) generally supports the conclusion reached by Johnson (1992) and Johnson and Curtis (2001) that soil carbon losses due to harvesting and site preparation are generally minor and followed by recovery. In addition, it appears that losses are related to the degree of ground disturbance resulting from the harvesting and site-preparation operations. However, some studies indicate that effects due to harvest may occur deeper in the profile or later in time than can be detected by most available studies, and results can vary with vegetation type, climate, and site fertility. Future studies on the impacts of harvesting and site preparation on SOC pools should be designed to take these results into account whenever possible.

PRESCRIBED FIRE AND WILDFIRE

Johnson's 1992 review surveyed 12 studies on the effects of fires, both wildfire and prescribed burning, on soil carbon; the updated review (Johnson and Curtis, 2001) adds an additional study. The 1992 review found that carbon losses from mineral soil, as a result of low-intensity prescribed fire, were minor or nonexistent. In some cases, soil carbon increased after burning as a result of invasion by nitrogen-fixing species. Wildfires, however, often resulted in significant carbon loss from the mineral soil, although some studies reported no changes. Generally, the effects on carbon were linked to fire intensity. The meta-analysis (of data from 13 studies) presented by Johnson and Curtis (2001) reaches a somewhat different conclusion. When all fire studies were combined, no significant fire response of the surface or whole soil was found. When the studies were separated into classes for analysis (0 to 5, 5 to 10, or 10+ years since fire) a different result emerged, with significantly higher carbon in the 10+ year postfire group. When just the studies in the 0 to 10 years postfire categories were considered, Johnson and Curtis found a significant fire effect for surface soils, but the opposite of the previous study — soil carbon was higher (relative to unburned areas) following wildfire and lower after prescribed fire. The results of the fire studies discussed below are summarized in Table 14.2.

Prescribed Fire: Southeastern United States

Binkley et al. (1992) investigated the effects of repeated burning on soils in a loblolly/longleaf pine forest in the Southeast. Plots had been established in 1959 and burned repeatedly according to their assignment to one of four fire intervals: 1, 2, 3, 4, or 0 (control) years. Plots were sampled in 1990 to depths of 0 to 10 and 10 to 20 cm. Bulk density was significantly higher in control vs. burned plots; the authors proposed no explanation. While some of the plots did differ in surface carbon content (0 to 10 cm), there was no trend related to burning interval. The C:N ratio did widen with decreasing burn interval, but these differences were not significant. The changes in bulk density are interesting to note and warrant further investigation. Another study in the Southeast measured changes in surface-soil chemistry after stand-replacement fires in pine-hardwood ecosystems (Vose et al., 1999). A steep, south-facing slope was burned without felling any vegetation in an attempt to reduce mountain laurel and stimulate pine-seed germination and oak regeneration. The uppermost 5 cm of mineral soil was sampled prior to the burn and 3 months afterward. Fire temperatures varied across slope positions, with the hottest temperatures generally on the ridge. No significant changes in soil carbon concentration were found at any slope position.

Table 14.1 Effects of Harvesting and Site Preparation on Soil Organic Carbon

Site/Forest Type	Silvicultural Treatment	Soil Depths Sampled	Quantity Reported/Analysis Method	Study Notes	Results	Reference
New Hampshire northern hardwoods	Clear-cut; slash piled	By horizon; 1 × 1.5-m pit; depths not given	SOC conc. by wet chemical; no BD data	Chronosequence: stands 3, 10, 30, and 93 years old	No sig. differences in conc. or cont.	Snyder and Harter, 1984
New Hampshire northern hardwoods	Whole-tree harvest	0–10 cm, 10–20 cm, 20-cm C horizon	SOM conc. by LOI; SOM cont.; BD data	Plots sampled prior to harvest and 3 years postharvest	No sig. differences in conc. or cont.	Johnson et al., 1991
New Hampshire northern hardwoods	Whole-tree harvest	0–10 cm, 10–20 cm, 20-cm C horizon; also by horizon	SOC conc. by dry combustion; SOC cont.; BD data	Plots sampled prior to harvest and 3 and 8 years postharvest	No sig. change 3 years postharvest; 8 years postharvest, sig. decrease in C cont. at 10–20 cm and 20 cm; no sig. change in total pool	Huntington and Ryan, 1990; Johnson et al., 1995
West Virginia mixed oak-hickory and northern hardwoods	Varied; mostly clear-cut with slash intact	0–10 cm	SOM conc. by LOI; SOM cont.; BD data	Paired plot study; 0.5–23 years postcut (15 pairs)	No sig. change in conc. or cont. overall; 4 cut sites showed SOM loss	Mattson and Smith, 1993
Kentucky oak dominated	Severe thin, 70–90% removal	0–15 cm	SOC conc. by wet chemical; no BD data	Paired plot; two forests of different soil nutrient status	No sig. difference in SOC at lower-quality site; thinned plots had sig. higher SOC at higher quality site	Morris and Boerner, 1998
Wisconsin sugar maple dominated	Heavy, medium, and light individual tree selection; diameter-limited cut	0–3 cm, 3–10 cm, 10–40 cm	SOC conc. by dry combustion; SOC cont.; no BD data	Randomized block design; replicated; no pretreatment soils data	Diameter-limited plots had sig. lower SOC content at 3- to 10-cm depth; lower SOC in more heavily cut plots, but not sig.	Strong, 1997
Minnesota and Michigan aspen	Varied harvest types, not detailed for each plot	Surface soil and "other soil to 25 cm"; also some 25–50-cm samples	SOC conc. by dry combustion; SOC cont.; no BD data	Chronosequence: 0–80 years; pre- and postharvest study	No sig. changes after harvest; no sig. changes through time; FF and soil data were treated together in statistics	Alban and Perala, 1992

Michigan black spruce swamp	Whole-tree harvest; whole-tree harvest plus bedding	By horizon to 50 cm; horizon depths given	SOC conc. by wet chemical; SOC cont.; no BD data	Randomized block design; replicated; no pretreatment soils data	No sig. differences in SOC conc., but SOC cont. to 50 cm was sig. lower in harvest plots than in control or bedded plots, which did not differ	McLaughlin et al., 1996
Virginia loblolly pine plantation	Clear-cut and planted	0–10 cm and 10–33 cm	SOC conc. by wet chemical; SOC cont.; no BD data	Chronosequence: 11 sites; 1–26 years old	No sig. differences in SOC cont. at either depth across the chronosequence	Schiffman and Johnson, 1989
Tennessee mixed deciduous, oak dominated	Whole-tree harvest, sawlog-only harvest	0–15 cm, 15–30 cm, 30–45 cm	SOC conc. by wet chemical and dry combustion; SOC cont.; BD data	Replicated treatment watersheds; pre- and postharvest soils data	No sig. differences in SOC cont. between treated and control watersheds prior to or postharvest (5 months or 15 years)	Edwards and Ross-Todd, 1983; Johnson and Todd, 1998
North Carolina mixed deciduous, oak-hickory prevalent	Whole-tree harvest, sawlog-only harvest	0–10 cm, 10–30 cm, 30–60 cm	SOC conc. by dry combustion; SOC cont.; BD data	Preharvest soils data not given	No declines in SOC apparent 5–8 years postharvest	Mattson and Swank, 1989
Alabama water tupelo-bald cypress wetland	Skidder logged, helicopter logged, or helicopter logged with herbicide	0–20 cm	SOM conc. by LOI; no BD data	3 × 3 Latin square with separate block of reference plots	Sig. lower SOM in all harvest plots; helicopter-logged plus herbicide plots lowest; by 2 years postharvest, only helicopter-logged plus herbicide sig. different	Aust and Lea, 1991
South Carolina loblolly pine plantation	Clear-cut; no details given on slash	0–10 cm, 10–30 cm, 30–50 cm	SOC conc. by dry combustion; SOC cont.; no BD data	Treated and reference sites; soils sampled 0–13 years postharvest	13 years postharvest, SOC conc. in 0–10 cm and 10–30 cm sig. higher than uncut stand	Van Lear et al., 1995
Washington Douglas-fir/alder	Harvest and species conversion	0–7 cm, 7–15 cm, 15–30 cm, 30–45 cm	SOC conc. by dry combustion; SOC cont., no BD data	Species conversions: fir/fir, fir/alder, alder/alder, alder/fir; pre- and postharvest (7 years) data	Fir/fir: no sig. change Fir/alder: increase (27%), not sig. Alder/alder: sig. decline Alder/fir: decline, not sig.	Cole et al., 1995

Table 14.1 Effects of Harvesting and Site Preparation on Soil Organic Carbon ***(Continued)***

Site/Forest Type	Silvicultural Treatment	Soil Depths Sampled	Quantity Reported/Analysis Method	Study Notes	Results	Reference
Alberta, Canada spruce-aspen	Clear-cut and site prep: disking, ripping, blading	0–7 cm, 20–27 cm	SOC conc. by dry combustion; no SOC cont.; no BD data	No pretreatment soils data; sampling done 20 months postharvest; replicates	No sig. harvest effects at either site; at more fertile site, all site-prep plots had sig. lower SOC in 0–7 cm and also 20–27 cm; at less fertile site, only bladed plots had sig. lower SOC in 0–7 cm	Schmidt et al., 1996
Ontario, Canada planted white pine/white spruce	Clear-cut and slash intact/bladed, fertilized/not fertilized, herbicide/no herbicide	0–10 cm	SOC conc. by wet chemical; no SOC cont.; no BD data	Randomized block, split plot; no initial soils data given; unclear if pretreatment data were taken	No significant effects of any treatment detected 4 years after treatments applied	Munson et al., 1993
Ontario, Canada pine-aspen	Whole-tree harvest, sawlogs only	0–5 cm, 5–10 cm, 10–20 cm	SOM conc. by LOI; SOM cont.; no BD data	Uncut stand used as reference; no pretreatment data	No significant differences between treatments or reference	Hendrickson et al., 1989
Saskatchewan, Canada aspen-spruce	Clear-cut	0–15 cm, 15–30 cm, 30–45 cm; surface organics included in 0–15-cm layer.	SOC conc. by dry combustion; SOC conc.; BD data for some sites	Chronosequence: 17 sites 1–19 years old and mature stands	Clear-cut sites showed sig. higher SOC conc. than mature sites 0–5 years postcut; sites in the 6- to 20-year postcut category had sig. less SOC relative to mature sites	Pennock and van Kessel, 1997

Note: SOC, soil organic carbon; SOM, soil organic matter, contains carbon, nitrogen, and other elements; wet chemical, Walkley-Black method and other similar wet chemical methods; dry combustion, modified Dumas method performed on such instruments as a Leco C analyzer, Carlo-Erba CN analyzer, etc.; LOI, loss-on-ignition method (used for SOM only); BD, bulk density; conc., concentration; cont., content; sig., significant; FF, forest floor.

Table 14.2 Effects of Prescribed Fire and Wildfire on Soil Organic Carbon

Site/Forest Type	Fire Regime	Soil Depths Sampled	Quantity Reported/Analysis Method	Study Notes	Results	Reference
South Carolina loblolly/longleaf pine	Prescribed fire: 1-, 2-, 3-, or 4-year interval; plots established 1959	0–10 cm, 10–20 cm	SOC conc. by dry combustion; SOC cont.; BD data	Plots are replicated; no pretreatment data available; plots sampled in 1990	No clear trends for SOC conc. or cont.; control plots had slightly lower C:N than burned plots, but not sig.	Binkley et al., 1992
North Carolina pine-oak	Prescribed fire, variable flame temp., mostly 700–800°C	0–5 cm	SOC conc. by dry combustion; no BD data	Pre-and postburn samples taken; plots replicated	3 months postburn, no sig. differences ($P < 0.10$) at any slope position	Vose et al., 1999
Missouri oak-hickory	Annual spring burn or 4-year periodic burn	0–15 cm	SOC conc., method not specified; no BD data	Pre-and postburn samples taken; plots replicated	No differences between burning treatments or burned and control plots	Eivazi and Bayan, 1996
Oregon ponderosa pine	Prescribed spring underburning, low intensity	0–5 cm, 5–15 cm	SOC conc. by dry combustion; no BD data	Chronosequence: 5 sites; 0–12 years postburn; control plots at each site	Plots 4 months postburn had sig. higher SOC conc. ($P = 0.017$); 5-year postburn site had sig. lower SOC conc. ($P = 0.043$)	Monleon et al., 1997
Oregon and Washington Douglas-fir	Prescribed fire for slash reduction in 1947–1950	0–10 cm	SOM conc., method not specified; no BD data	Paired plot study: 34 burned/unburned pairs on transect	No effect of burning; sig. difference due to geographic location for both burned/unburned plots	Kraemer and Hermann, 1979
Montana ponderosa pine	Combination study: control, selection cut, or cut+burn	7.54 cm or 10 cm, depending on site	SOC conc. by dry combustion; no BD data	3 sites considered as separate cases; treated 0, 2, or 11 years prior to sampling	Year-0 site had sig. higher SOC conc. in surface soil of cut+burn; year-11 site had sig. lower SOC conc. in cut+burn	DeLuca and Zouhar, 2000

Table 14.2 Effects of Prescribed Fire and Wildfire on Soil Organic Carbon ***(Continued)***

Site/Forest Type	Fire Regime	Soil Depths Sampled	Quantity Reported/Analysis Method	Study Notes	Results	Reference
British Columbia, Canada lodgepole pine	Site prep: windrow+burn or broadcast burn; four fire classes (low–high severity)	0–15 cm	SOC conc. by dry combustion; no BD data	Randomized block; unequal number of plots; only two control plots; seedlings planted in treatment plots	No sig. difference in SOC conc. between site-prep treatment or fire severity 5 years postburn	Blackwell et al., 1995
Victoria, Australia eucalyptus	Prescribed fire: varied fuel loads 0, 15, 50, 150, or 300 t/acre	0–2 cm, 2–5 cm, 5–10 cm	SOC conc. by wet chemical; BD data	Plots not replicated; pre- and postburn samples taken	0–2-cm depth, SOC conc. sig. lower; decline related to fuel load; slight reduction in 2–5-cm depth for burned plots but not sig.	Tomkins et al., 1991
Wildfire						
Alaska black and white spruce, aspen, birch	Wildfire: sampled unburned, lightly burned and heavily burned areas	0–5 cm	SOM conc. by LOI; SOM cont.; no BD data	Spruce plots had all three burn classes; aspen and birch had control and light burn only	No statistics included, but black spruce sites had higher SOM in burned plots; burned aspen plots had lower SOM	Dyrness et al., 1989
Washington ponderosa pine/Douglas-fir and lodgepole pine/Englemann spruce	Wildfire: pine/fir site, ranged from light surface to severe crown; pine/spruce was severe crown	By horizon; horizon depths are given for each site	SOC conc. by dry combustion; SOC cont.; no BD data	Pine/fir site was seeded with grass and fertilized; no rehab at pine/spruce site; little revegetation at time of sampling	In pine/fir, SOC cont. sig. lower in all horizons — both 3 months and 1 year postfire — compared with unburned areas; in pine/spruce, no sig. difference and very high variability	Baird et al., 1999

Ontario, Canada jack pine	Severe wildfire	0–2 cm, 2–6 cm, 28–32 cm, 32–42 cm	SOM conc. by LOI; no BD data	Sampled 3 and 15 months after fire	3 months after fire, 0–2 cm had sig. lower SOM; by 15 months, all depths had small but sig. (P = 0.01) increase in SOM	Smith, 1970
NW Spain Scotch pine	High-intensity wildfire	0–5 cm, 5–10 cm	SOC conc. by dry combustion	Sampled 1 day after fire; unburned area also sampled	In each depth, SOC conc. was ca. 50% lower in burned areas relative to unburned	Fernandez et al., 1997
SE Spain mixed pines	Wildfire: varied fire intensity, low to high	0–5 cm	SOC conc. by dry combustion; no BD data	Five sites with three fire intensities; sampled 9 months postfire	In four of the sites, SOC conc. was sig. lower than paired unburned areas	Hernandez et al., 1997
NW Spain Scotch pine and maritime pine	Wildfire: high intensity, heated soil to 5 cm	0–5 cm, 5–10 cm	SOC conc. by dry combustion; no BD data	Two sites in different climatic zones, sampled over 2 years	Sig. initial decrease in SOC conc. at both sites, larger at high-elevation site; 0–5 cm recovered by 2 years at both sites but 5–10 cm lower than unburned soils	Fernandez et al., 1999

Note: SOC, soil organic carbon; SOM, soil organic matter, contains carbon, nitrogen, and other elements; wet chemical, Walkley-Black method and other similar wet chemical methods; dry combustion, modified Dumas method performed on such instruments as a Leco C analyzer, Carlo-Erba CN analyzer, etc.; LOI, loss-on-ignition method (used for SOM only); BD, bulk density; conc., concentration; cont., content; sig., significant; FF, forest floor.

Prescribed Fire: Central United States

A different approach was used in an oak-hickory forest in Missouri, where Eivazi and Bayan (1996) looked at the effects of long-term prescribed fire on soil enzyme activity in unburned, annually burned, and periodically burned plots that had been treated since 1949. Although the surface soil carbon concentrations were not significantly different between treatments, it is interesting to note that there was a significant decrease in microbial biomass with increased fire frequency. Activity of several key enzymes involved in N, P, S, and C cycling was also significantly reduced in the long-term burning plots.

Prescribed Fire: Northwestern United States

In central Oregon, Monleon et al. (1997) investigated short- and long-term effects of underburning in ponderosa pine stands. Several sites were used: 12 and 5 years postburn, 4 months postburn, and an unburned control. Soils were sampled to depths of 0 to 5 and 5 to 15 cm. Compared with controls, 4-month plots displayed significant increases in carbon concentrations ($P = 0.017$); year-5 plots showed significant decreases ($P = 0.043$); and year-12 plots were not significantly different from controls at the 0- to 5-cm depth. No significant changes were noted for the 5- to 15-cm layer, and no bulk-density information was reported. Kraemer and Hermann (1979) measured organic matter in 34 pairs of burned and unburned plots in Douglas fir forest-in the western Cascade Mountains after 25 years of broadcast burning to reduce slash. Plot area was stratified into burn classes (light, moderate, and severe), and the surface 0 to 10 cm of soil were sampled. Surface organic-matter concentrations did not differ between burn-severity classes or between burned and unburned plots. The only significant difference in organic-matter concentrations occurred between plots in the North Cascades, which had significantly lower organic-matter concentrations than those in the South Cascades, regardless of burning status.

DeLuca and Zouhar (2000) investigated the effects of a combination of selection harvest and prescribed fire on chemical properties in ponderosa pine in western Montana. Three separate sites were used, representing 0, 2, and 11 years posttreatment; no pretreatment soils data are available. Each site received three treatments: control, selection harvest (11.5 m^2/ha residual), and selection harvest with prescribed burning. Soil carbon concentrations were significantly higher in the cut-and-burn treatment than in either the control or selection-cut-only treatments (which had similar SOC values) at the site treated that year, while at the 2-year posttreatment site, carbon concentrations did not differ across treatments. Results from the 11-year posttreatment site are the opposite of the zero-year site: SOC concentrations were significantly lower in the cut-and-burn plots but did not differ between the control and selection-cut-only plots. Unfortunately, it is not possible to determine if the differences are a result of the time since treatment or the inherent site characteristics, but this study does suggest that the combined effects of treatments may differ from the effects of individual treatments in ways that can be difficult to predict.

Prescribed Fire: Other Nations

In British Columbia, prescribed fire was used to convert overstocked lodgepole pine stands into plantations (Blackwell et al., 1995). Site preparation consisted of windrowing slash followed by burning or broadcast burning of slash. For each site-preparation treatment, four fire types were used: low severity in fresh slash, low severity in cured slash, moderate severity, and high severity. Five years after burning, percent carbon in the 0- to 15-cm layer did not differ across fire severity or site preparation treatment, nor was the C:N ratio affected. The exception was the low-severity cured-slash treatment, where the C:N ratio was significantly lower than in all other treatments.

The final prescribed-fire study we will consider was conducted in a eucalyptus forest in Australia, where soil chemistry following fires with different fuel loads was measured (Tomkins et al., 1991). Pre- and postburn samples were taken at depths of 0 to 2, 2 to 5, and 5 to 10 cm for the following fuel levels: 0 (control), 15, 50, 150, and 300 t/ha. Significant decreases in carbon content of the 0–2-cm layers were found (P = 0.01), with the magnitude of the loss proportional to the fuel load (at the 300-t/ha load, a 42% loss was reported). Reductions in the 2- to 5- and 5- to 10-cm layers were also reported (but were not significant) and were not related to fuel load. One interesting result, in contrast to the findings of Binkley et al. (1992), was a significant increase in postburn bulk density in the 0- to 2-cm soil layer.

Wildfire: Alaska and Northwestern United States

The effect of wildfire on soil chemistry was assessed for four forest types in Alaska (Dyrness et al., 1989). The sites were located in the Bonanza Creek Experimental Forest and represented the following types: black spruce, white spruce, aspen, and paper birch. Areas in the spruce types were classed as lightly or heavily burned, while aspen and birch areas were only lightly burned. Unburned areas with similar characteristics were used as control plots for each forest type. Measurements of the upper 5 cm of mineral soil were made immediately following the fire. Unfortunately, there was insufficient site replication, so no analysis of variance could be performed. Results were not consistent and differed across forest types; white spruce sites showed no fire effect, while black spruce plots displayed increased carbon content under both burn intensities, with the lightly burned plots having the greatest increase. Lightly burned aspen soils contained less surface-soil carbon than control plots, while the opposite was true for birch sites, although the changes in birch soils were small.

Wildfire effects in the eastern Cascades were studied by Baird et al. (1999), who measured soil-chemistry changes in ponderosa pine/Douglas-fir and lodgepole pine/Engelmann spruce forests in Washington. In the ponderosa pine forest, fire severity ranged from slight to severe; seeding of grasses occurred in the most severely burned areas. Soils were sampled at 3 months and again at 1 year postfire and compared with samples taken at the same time from unburned areas. Soil carbon content was significantly lower in burned areas at both 3 months and 1 year postfire in both the A and B horizons. In the lodgepole pine forest, a severe crown fire occurred. Sampling occurred 1 year following the fire, and burned areas had lower SOC content in the A horizon, but due to higher site variability the decrease was not statistically significant. The decrease in soil carbon stocks from fire was estimated to be 25 Mg/ha for the ponderosa pine forest, and 7 Mg/ha in lodgepole pine; the authors also estimated carbon loss due to the sheet and rill erosion that occurred following the fires. Carbon loss through erosion during the 1-year period postfire was calculated to be 280 kg/ha at the ponderosa pine site and 640 kg/ha at the lodgepole pine site. Losses through erosion are frequently not computed in studies of fire effects, but can be a substantial source of carbon loss, especially in areas with steep slopes that suffer total loss of the surface organic layer.

Wildfire: Canada

In Ontario, Smith (1970) assessed the effects of a severe fire in a jack pine forest, conducting repeated measurements of organic matter to a depth of 42 cm for a period of 15 months following the fire. Three months following the fire, organic-matter concentrations in the 0- to 2-cm depth were lower than before the fire; no effect was seen at lower depths. At 15 months after the fire, small but significant increases in SOM concentration had occurred at all depths. The authors suggest that this may be partly due to the invasion of the area by grasses and sedges following the destruction of existing surface vegetation during the fire.

Wildfire: Mediterranean Nations

Several studies assessing the effects of wildfire on forest-soil chemistry have been conducted in Spain. Fernández et al. (1997) measured changes in organic matter after a high-intensity wildfire in a Scotch pine forest. Soils were sampled one day after the fire at depths of 0 to 5 and 5 to 10 cm, and nearby unburned areas of similar vegetation were used as controls. Losses of organic matter were roughly 50% for the entire 0- to 10-cm depth. Changes in the chemistry of organic matter in burned and unburned areas were also found, with the largest differences found in the 5- to 10-cm layer, where fire significantly reduced the amount of cellulose and hemicellulose compounds. Lignins were also reduced in burnt soils at both depths. In addition, the carbon mineralization rate was significantly higher in burnt soils. Changes in organic-matter chemistry after fire warrant further investigation, since the various carbon-containing compounds have very different residence times.

In southeastern Spain, Hernández et al. (1997) sampled soils at five pine forest sites 9 months after wildfire. Three sites experienced fires with temperatures of 300 to 350°C, one site had fire temperatures of about 250°C, and the fifth was a low-intensity fire with temperatures of about 100°C. In all but one site, concentrations of organic carbon were significantly lower in burned soils relative to unburned areas at each site. Interestingly, the one site with no significant difference was not the low-intensity fire site but one of the three sites that experienced severe fire. Changes in carbon chemistry were also noted in this study, with carbohydrates, fulvic acids, lipids, and water-soluble carbon significantly decreased (relative to other carbon fractions) in burned soils; this effect was seen regardless of fire intensity.

Wildfire effects have also been studied in pine forests in northwestern Spain; Fernández et al. (1999) measured soil carbon five times over a 2-year period following fire in a low-elevation (140 m) pine forest and a higher-elevation (1740 m) pine forest; samples were also taken from unburned areas at each site. At each site, the fire occurred in the summer and was intense: all trees were killed, and it was estimated that the fire penetrated 5 cm into the mineral soils (the depths sampled were 0 to 5 and 5 to 10 cm). There was a significant near-term decrease in SOC concentrations in both depth increments at both sites. For the high-elevation site, this amounted to about a 50% decrease in both depths, relative to controls. Losses at the low-elevation site were smaller and recovery was rapid, with SOC levels exceeding those in unburned soils by 4 months postburn. However, while SOC concentrations at the high-elevation site continued to recover, with surface soils reaching the values for unburned areas by 2 years after the fire, the subsurface SOC concentrations in the low-elevation forest declined between 12 and 24 months following the fire. At both sites, the subsurface soils had not recovered to the carbon levels found in unburned soils by 24 months postfire. During the 2-year study period, revegetation was sparse, which may partially explain the patterns seen in the subsurface layer.

Prescribed Fire and Wildfire: Conclusions

Few prescribed-fire studies specifically designed to measure changes on soil carbon exist, and wildfire studies, by their nature, must rely on paired-plot and chronosequence approaches and frequently lack the necessary replication for strong statistical treatment. Based on the studies cited here, prescribed burning appears to have little effect on soil carbon concentrations; reported effects were generally short-lived and confined to the surface layer. Contrary to the results of the analysis by Johnson and Curtis (2001), the papers reviewed here generally demonstrate a decrease in soil carbon or organic matter as a result of wildfire. Although it seems obvious that the degree of carbon loss would be related to fire intensity, this was often not the outcome seen in the studies reviewed here. In some instances, decreases were quite substantial (up to 50% of SOM) and were seen in subsurface as well as surface layers. The slow recovery reported in some studies may be related to the course of revegetation. Different patterns were observed between similar forest types at different elevations and geographic locations within a region. It is likely that the response of forest soils to wildfire is the result of interactions between forest type, climate, initial soil conditions, the presence/absence of vegetative recovery, elevation, and other factors. Carefully designed studies of different fire intensities, conducted in a range of forest types, will clarify the relationship between fire characteristics and soil carbon response. One factor rarely discussed in fire studies is the role of charcoal; since charcoal is quite recalcitrant, this may constitute a stable pool of carbon in the soil that can persist centuries after the fire event. Whether or not carbon fixed as charcoal is a significant carbon pool is not known, but this may well be a factor worth considering in the design of future studies of fire effects on forest carbon pools.

FERTILIZATION AND LIMING

Both of Johnson's reviews found that fertilization and interplanting with nitrogen-fixing species resulted in increases in soil carbon pools. Other studies not cited in those reviews support that finding. Since forest-fertilization studies that include soil-carbon response are fairly rare, some grassland-fertilization studies are also included. Table 14.3 presents a summary of the results from the papers below, excluding the studies relating only to the effects of fertilization or liming on greenhouse-gas emissions.

Fertilization and N-Fixing Species

Neilsen and Lynch (1998) studied a stand of radiata pine in Tasmania that had been fertilized with 100 kg/N on an annual basis from 16 to 28 years after stand establishment. While SOC concentrations in the 0- to 10-cm depth declined with time in the control plots, concentrations in the fertilized plots increased during treatment, although they began to decline after fertilization ended. A grassland study conducted in Saskatchewan (Nyborg et al., 1999) found significant increases in SOC content, relative to control plots, after annual applications of nitrogen plus sulfur fertilizers for 13 years. An interesting part of this study was the assessment of light-fraction organic carbon, believed to been a fast-cycling pool. Much of the SOC increase was in the light-fraction organic carbon pool, suggesting that gains in soil carbon from fertilization may be short-lived. In another Canadian grassland study, Malhi et al. (1991) measured soil chemical properties in a bromegrass field that had been fertilized annually for 16 years. Fertilizer was applied in the spring at eight different rates ranging from zero to 336 kg N/ha. Soil samples were taken in varying depth increments from zero to 120 cm; increases in SOC concentrations were seen in the 0- to 5-, 5- to 10-, and 10- to 15-cm depths at all levels of fertilization (the lowest was 56 kg N/ha), with the largest increases in the 0- to 5-cm layer.

A study established on old sugar cane fields in Hawaii (Kaye et al., 2000) assessed the effects of varying mixtures of eucalyptus and an N-fixing species, *Albizia.* The proportions of *Albizia* in the experimental units were 0, 25, 34, 50, 66, and 100%; soil samples were collected to a depth of 50 cm 16 years after planting the stands. Soil organic carbon concentrations increased linearly with an increase in the percent *Albizia* in the stand ($r^2 = 0.87$). The authors also used stable-isotope analysis to assess the relative age of the carbon in the treatments; results indicated that the higher the percentage of *Albizia*, the higher was the proportion of "older" carbon, suggesting that intercropping with this N-fixer decreased carbon turnover.

Although the trend of increased soil carbon after fertilization is well-supported in the literature, some long-term fertilization studies have failed to find an effect. Harding and Jokela (1994) studied the effects of three treatments: control, with no fertilizer; OSP + NK (39 kg P/ha as ordinary superphosphate, 112 kg N/ha as NH_4NO_3, and 46 kg K/ha as KCl); and GRP (314 kg P/ha as ground rock phosphate). Fertilizers were applied at time of planting to a slash pine plantation in Florida, and soils were sampled when the plantation was 25 years old. Samples were taken at the following depths: 0 to 15, 15 to 31, 31 to 46, 46 to 61, and 61 to 91 cm. While fertilization significantly increased the forest-floor organic-matter pool, no significant differences were found in the mineral soil for any treatment at any depth.

Table 14.3 Effects of Fertilization and Liming on Soil Organic Carbon

Site/Forest Type	Treatment	Soil Depths Sampled	Quantity Reported/Analysis Method	Study Notes	Results	Reference
Tasmania, Australia radiata pine	100 kg N/ha/year from age 16–28	0–10 cm, 10–20 cm, 20+ cm	SOC conc. by wet chemical. No BD data	Replicated plots	SOC conc. in 0–10 cm of fertilized plots increased relative to controls; SOC conc. began to decline when fertilization ended	Neilsen and Lynch, 1998
Saskatchewan, Canada grassland	Annually: 112 kg N/ha, 11 kg S/ha, N+S, N+S+40 kg K/ha, or control	0–2.5 cm, 2.5–5 cm, 5–10 cm, 10–15 cm, 15–30 cm	SOC by dry combustion, SOC cont. No BD data	Replicated but not randomized; 13-year treatment duration	Sig. increase in SOC cont. in N+S treatment only; sig. for 0–2.5- and 15–30-cm depths and for total 0–30-cm depth	Nyborg et al., 1999
Alberta, Canada bromegrass	Annually: 56, 84, 112, 168, 224, 280, or 336 kg N/ha, or control	0–5 cm, 5–10 cm, 10–15 cm, 15–30 cm, 30–60 cm, 60–90 cm, 90–120 cm	SOC conc. by dry combustion. No BD data	Randomized block design, replicated; 16-year treatment duration	Sig. increase in SOC conc. in 0–5-, 5–10-, and 10–15-cm depths at all rates of N application	Malhi et al., 1991
Hawaii eucalyptus/*Albizia*	Interplanting of N-fixing species: 0, 25, 34, 50, 66, or 100% of trees	0–50 cm	SOC conc. by dry combustion, SOC cont. No BD data	Randomized block design; sampled 16 years after establishment	SOC cont. increased linearly with increasing proportion of N-fixing species (r^2 = 0.87)	Kaye et al., 2000

Florida slash pine plantation	Time of planting: 39 kg P/ha+112 kg N/ha+46 kg K/ha, or 314 kg P/ha or control	0–15 cm, 15–31 cm, 31–46 cm, 46–61 cm, 61–91 cm	SOC conc. by wet chemical, SOC cont. No BD data	Randomized block design installed 1961; sampled when 25 years old	No sig. (at alpha = 0.10) differences between any treatments or controls at any depth for SOC conc. or cont.	Harding and Jokela, 1994
Washington Douglas–fir	896–1120 kg N/ha over 12–16 years, depending on the site	A horizon, then top of B horizon to 25 cm, 25–55 cm, 55–85 cm	SOC conc. by dry combustion, SOC cont. No BD data	Three sites; one control and one fertilized plot at each. Stands 30–40 years old at time of fertilization, 60–70 years when sampled	No significant differences in SOC cont. between control and fertilized plots at any depth at any site	Canary et al., 2000
Sweden Scotch pine	150 kg N/ha or 600 kg N/ha, as urea or NH_4NO_3 (four possible combinations)	A horizon	SOC by dry combustion, SOC cont., no BD data	Two sites; soil data for only one site; replicated design	No sig. differences between any treatment or control for surface soil SOC conc.	Nohrstedt et al., 1989
Southern Sweden Norway spruce and European beech	Varied rates, generally 9–10 t/ha $CaCO_3$	0–10 cm, 10–20 cm, 20–30 cm, 30–50 cm	SOC conc. by dry combustion, SOC cont., no BD data	Four sites; two had replicate plots; treated in 1951–55	Decreases in total profile SOC pool, but driven by forest floor; mineral soil only shows no or slight decrease in SOC cont.	Persson et al., 1995

Note: SOC, soil organic carbon; SOM, soil organic matter, contains carbon, nitrogen, and other elements; wet chemical, Walkley-Black method and other similar wet chemical methods; dry combustion, modified Dumas method performed on such instruments as a Leco C analyzer, Carlo-Erba CN analyzer, etc.; LOI, loss-on-ignition method (used for SOM only); BD, bulk density; conc., concentration; cont., content; sig., significant; FF, forest floor.

In another long-term study, Canary et al. (2000) evaluated carbon sequestration in second-growth Douglas-fir stands that had been fertilized with urea several times over a 16-year period. Two of the sites received a total of 896 kg N/ha and a third was given 1120 kg N/ha; stands were 30 to 40 years old when treatment began. While total stand-level carbon storage increased as a result of fertilization, this was mainly due to increases in overstory biomass. No differences in soil carbon content between the control and fertilized plots were detected at any depth. In Sweden, two pine forests were subjected to various fertilizer treatments (Nohrstedt et al., 1989). Plots in a 125-year-old forest were treated in 1974 with 150 or 600 kg N/ha, while a 45-year-old site was fertilized with 150 kg N/ha in 1977 and 1984. The sites were sampled in 1985, but surface mineral soils were taken only at the 125-year-old site (samples from the 45-year-old site included just the litter layer). For surface mineral-soil carbon, SOC concentrations did increase slightly, but there were no significant differences between treatments and the control.

Effects of Fertilization on Greenhouse-Gas Emissions from Soil

While forest fertilization may increase soil carbon pools (and does increase stand-level carbon stocks), when looking at carbon from a sequestration point of view, the entire carbon cycle must be considered as well as cycles of other greenhouse gases. A hidden cost of forest fertilization may be increased emissions of N_2O and decreased absorption of CH_4 (as well as the emissions produced during manufacture and application of the fertilizer); both of these gases have warming potentials much higher than that of CO_2.

Castro et al. (1994) studied the effects of nitrogen fertilization on the fluxes of several greenhouse gases from pine soils in a Florida plantation. Between 1987 and 1991, plots were fertilized quarterly with an NPK fertilizer; an additional 180 kg N/ha was added annually as urea. Other plots in the same plantation were established as controls. Gas sampling for N_2O, CH_4, and CO_2 was conducted in February, May, and November of 1991. On all three sampling dates, there were no significant differences in CO_2 emissions between fertilized and unfertilized plots. However, N_2O emissions were significantly higher (8 to 600 times; 12.29 to 72.19 μg N_2O-N/m²/h, depending on sampling date) from fertilized plots on all sampling dates, while CH_4 uptake in fertilized soils was significantly lower (5 to 20 times; 0.014 to 0.343 mg CH_4-C/m²/h) than control soil on all dates. Soil temperature and moisture, which greatly influence microbial processes, did not differ significantly between fertilized and unfertilized plots.

Steudler et al. (1989) evaluated the effects of N fertilization on methane uptake by soils in red pine and black oak/red maple stands in Harvard Forest. Plots received either 0, 37, or 120 kg N/ha in several applications over a 6-month period. Methane uptake was measured from 1 month after the beginning of treatment through 1 month after the last N addition; after 6 months of fertilization, methane uptake rates in the fertilized plots were significantly lower than in controls. While declines in uptake were seen in both the hardwood and pine stands, the effect was greater in pine soils. Similar results were found by Sitaula et al. (1995) in Norway, where soils from a Scotch pine forest were incubated in lysimeters and treated with combinations of three levels of pH (3.0, 4.0, and 5.0), and three levels of N (0, 30, and 90 kg N/ha/year). At all pH levels, N fertilization significantly decreased the uptake of methane; the effect from the higher level of N was more than double that of the lower N treatment, regardless of pH. These results should serve as a caveat when considering operational forest fertilization to increase carbon sequestration in biomass or soil, since net greenhouse-gas emissions may increase rather than decrease as a result.

Liming of Acid Soils

Liming, however, may have the opposite effect of fertilization, increasing CH_4 uptake and decreasing emissions of N_2O. Although not a management technique commonly used in the United States, the practice has been investigated in Europe and Scandinavia. Borken and Brumme (1997) investigated the effects of varying doses of lime on acidified beech and spruce forests in Germany. Lime application rates varied: 4.5, 6, 7.5, 30, and 43 t/ha; not all rates were applied on all sites. All lime treatments occurred between 1980 and 1988. Nearby unlimed sites, similar in vegetation, were used as controls. Gas measurements were made between 1993 and 1995 on a weekly or biweekly basis. No significant differences in CO_2 emissions were found between limed and unlimed plots. In all but one of the five limed sites, N_2O emissions were lower in limed plots, but this difference was significant only in the two beech sites, which received high lime doses and which had the highest emissions in the absence of lime application. In four of the five sites, lime application increased CH_4 uptake by forest soils, and these differences were again significant for the beech sites, which had the lowest uptake in the absence of lime; the increase in uptake in these soils was substantial. The results of Borken and Brumme (1997) indicate that in acidified soils with low CH_4 uptake and high N_2O emissions, application of heavy doses of lime may reduce greenhouse-gas emissions from the soil.

Effects of liming on soil carbon pools are not so clear. Persson et al. (1995) looked at the effects of liming in Sweden on carbon pools and fluxes. Lime was applied to Norway spruce and European beech sites in the early 1950s at a rate of 9–10 t/ha. Samples were taken approximately 40 years after liming at depths of 0- to 10, 10- to 20, 20- to 30, and 30- to 50 cm, although most of the discussion in the paper centers on effects in the forest floor (L, F, and H layers). While limed plots often showed major decreases in the forest-floor carbon pool, there were no significant differences in the mineral-soil carbon pool of limed soils relative to controls. In addition, no effects on tree growth were reported. While liming acid forest soils to reduce greenhouse-gas emissions may be a useful strategy, further research is needed to quantify reduction potentials and to ascertain that carbon storage and tree growth are not affected by the practice.

SUMMARY AND CONCLUSIONS: SOIL CARBON SEQUESTRATION AND FOREST MANAGEMENT

A survey of available literature suggests that forest harvesting and regeneration, in the absence of major soil disturbance, does not lead to substantial changes in mineral-soil carbon storage. However, the evidence suggests that effects are likely to vary by geographic region (due to climatic influences), forest type, and other site characteristics (such as soil productivity). In addition, longer-term studies indicate that effects may occur at depth over a longer time frame than is traditionally studied. The assertion of no negative effects could more strongly be made if a series of well-designed, consistently executed harvest studies were conducted in various geographic regions over longer time intervals.

The results from the various fire studies reported are variable but suggest that prescribed fire, even when conducted repeatedly, has little effect on soil carbon stocks, and any effects are generally transitory. The literature on wildfire effects, on the other hand, indicates that losses of carbon and organic matter from the surface layers can be quite substantial, and the course of recovery may depend on the revegetation process. Reductions of soil carbon at depth were also reported following wildfire; in some cases, recovery to prefire levels was slow. Changes in the chemistry of organic carbon were also detected following wildfire. The effects of fire on the depth distribution and chemistry of carbon need to be further investigated to arrive at a clear understanding of the effects of fire on soil carbon stocks, and the influence of forest type also warrants further attention. As with harvesting, it is likely that forest type and local conditions will affect the outcome.

While most studies support the finding that fertilization increases soil carbon storage, there are tradeoffs in the form of increased N_2O emissions and decreased CH_4 absorption. To fully evaluate the effects of forest fertilization, complete greenhouse-gas budgets need to be constructed when conducting forest fertilization experiments. Fertilization may be a viable means to increase terrestrial carbon sequestration, but only if the gains exceed the losses, since both N_2O and CH_4 have higher warming potentials than CO_2. While liming of highly acidic forest soils may provide a means of reducing greenhouse-gas emissions, data are too scarce at this point in time to draw any conclusions about the effects of this practice, either in terms of carbon benefits or possible adverse effects on tree growth and nutrition.

In conclusion, both harvesting (followed by regeneration of forests) and prescribed burning, as they are generally currently practiced (and under the methods by which soils are currently studied and sampled), do not appear to have any significant or lasting effects on soil carbon stocks. Fertilization may increase soil carbon concentrations, but the results are also mixed. Wildfire appears to lead to losses of soil carbon both on the surface and at depth. In all cases, researchers should exercise caution when extrapolating experimental results from one geographic region to another and should be aware of interactions between treatments and local site variables.

LEARNING FROM THE PAST: RECOMMENDATIONS FOR FUTURE STUDIES

Our current knowledge, as previously discussed, is derived largely from studies originally designed to address other research problems. Recently, studies designed specifically to assess the effects of management practices on forest-soil carbon stocks have begun to appear in the literature, but what is still missing are studies designed to investigate management methods aimed at *increasing* the carbon stored in soils while remaining compatible with other traditional forestry objectives. To actively manage forest soils as a carbon sink, forest-soil researchers must design and test treatments using studies that are sufficiently robust to detect treatment effects. We can never completely overcome the problems of spatial heterogeneity and long timescales, but there are steps that can be taken to maximize the information we can gain from new studies. Based on the caveats discussed previously, I offer the following general recommendations:

- Maximize replication. This is what determines the ability to detect treatment effects, and it is especially critical in a spatially variable medium such as soil. When allocating resources, it is important to bear in mind that statistical power comes from the number of plots sampled rather than the number of holes per plot (D. Randall and S. Duke, personal communication); therefore, it is generally better to sample four holes in five plots than to sample ten holes in two plots. When conducting chronosequence studies, every effort should be made to establish two spatially independent "replicate" chronosequences.
- Report soil carbon concentration, bulk density, and soil carbon content. Bulk-density measurements, while they can be time consuming, are not technically difficult and do not require expensive equipment. Reporting all three quantities provides a clearer picture of how the soil system is responding.
- Analyze soil organic carbon concentration using a dry-combustion method, as recommended by Sollins et al. (1999). This is accepted as the standard method, and will avoid the over- and underestimations that can occur when using wet-oxidation methods or conversion from loss-on-ignition data (as discussed in the beginning of this chapter). Use of a standard method will also facilitate cross-comparison between studies.
- Separate the forest floor (L, F, and H layers) from the mineral soil; analyze samples and report results separately. While it is not always possible to separate the three layers of the forest floor (if all are present), generally the distinction between mineral soil and forest floor can be made. Neither pool should be disregarded, but in studies focusing on the response of soil to a treatment, inclusion of any portion of the forest floor complicates interpretation of the results, since the amounts of carbon and dynamics of the carbon cycles are extremely different between the two pools. Inclusion of all or part of the forest floor with the mineral soil also makes cross-comparison with other studies nearly impossible. When such a separation is difficult due to mixing of the forest floor and mineral soil from ground disturbance, this circumstance should be clearly noted. (However, sieving of soil through a 2-mm screen will help remove included organics from a soil sample.)
- Report sampling-depth increments clearly. If sampling by horizon, report horizon depths in appropriate units so that other investigators can estimate carbon content on a depth basis. In general,

when attempting to detect treatment effects, especially over a short period of time, the first sampling interval should be fairly shallow, such as 0 to 5 cm. Hopefully, over time, a standardized depth-based sampling protocol will emerge, greatly increasing our ability to draw conclusions from multiple studies conducted by many investigators. I would suggest a sampling protocol of 0 to 5, 5 to 10, and 10 to 20 cm as a starting point.

- Clearly describe the sampling design, including how samples were composited (if compositing occurred). Explaining how and why a particular sampling plan was adopted will provide other investigators with enough information to assess the adequacy of the design, as well as supplying information that will help in planning other experiments. Providing an analysis of statistical power, where possible, will greatly aid in the design of future studies. In cases where substantial soil disturbance has occurred as a result of management activities, clearly describe the type and extent of the disturbance and explain how this was addressed in the sampling plan. In general, it is probably best to stratify samples from disturbed and undisturbed areas if the level of soil disturbance is high (leading to a change in bulk density, or causing incorporation of forest floor into mineral soil) so that results can be clearly interpreted, rather than compositing such samples together.
- Carefully consider the costs of committing Type I and Type II errors. Many studies use the traditional significance value of alpha = 0.05. In a system as heterogeneous as forest soils, where it may not be possible to take a sufficient number of samples to detect a treatment effect, perhaps a different balance between Type I and Type II errors is needed. Each investigator should decide, for their particular study, what the appropriate level of significance should be. Peterman (1990) and Foster (2001) provide clear discussions of this topic.
- Plan studies of management effects over a sufficiently long time period. Again, some longer-term studies have shown no effects in the short term (0 to 10 years) but have recorded declines in soil carbon pools 15 to 20 years after treatment. Providing for longer-term follow-up sampling can add great value to a study, resulting in detection of trends that may have otherwise been missed.
- Archive soils from current studies. Storing 50 to 100 g of dried soil in an appropriate container will allow for re-analysis if methods change over time and will also permit comparative studies in the future. Samples should be stored in a secure location, with adequate documentation on sampling methods, study design, treatments applied, sample plot location, and the results of any chemical analyses performed. The problem of where to store samples so that future researchers are aware of their existence and have access to them also needs to be resolved. There is more than one case of a researcher archiving soils only to have them discarded years in the future, when the laboratory location is moved or the investigator has retired. Archived soils have great value and need to be adequately documented to ensure their preservation.

While there is no one-size-fits-all experimental design for soil studies, careful planning can yield studies that are robust and able to detect treatment effects, studies that will enable investigators to draw strong conclusions about the effects of management practices on soil carbon dynamics. Studies should also be designed, as much as possible, to facilitate comparison with the work of others. Since forest soils are unlikely to respond to management in a uniform manner, cross-comparison between studies conducted in different geographic regions and in forests of different types and ages is key to advancing our understanding of the soil carbon cycle. This understanding is critical if we are to realize the opportunities available to actively manage forest soils to promote carbon sequestration.

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