CLIMATE ACTION RESERVE

Accounting for Carbon in Soils

Prepared by

Alexander Gershenson, Ph.D.
James Barsimantov, Ph.D.
and
EcoShift Consulting, LLC

eco·shift CONSULTING
http://www.ecoshift.com

Table of Contents

Executive Summary 2

Acknowledgements 4

List of Important Terms 5

1. Introduction 6

   a. Basic factors affecting soil carbon dynamics 7

   b. Soil carbon sequestration issues in forests: Projections for overall sequestration potential 9

   c. Uncertainty in Soil Carbon Science 10

   d. Effect of site-specific factors, such as soil fertility and precipitation regimes on soil carbon 12

2. Effects of Pre-Harvest Management Techniques on Soil Carbon 14

   a. Fertilization and Competing Vegetation Control 14

   b. Mechanical Thinning 17

   c. Conclusion 19

3. Effects of Harvest Management Techniques on Soil Carbon 20

   a. Harvesting Techniques 20

   b. Harvest Intensity 22

   c. Rotation Length 24

   d. Conclusions 26

4. Effects of Post-Harvest Management Techniques on Soil Carbon 28

   a. Physical Disturbance 28

   b. Dissolved Organic Carbon 29

   c. Post-logging Debris Management 29

   d. Site Preparation 30

5. Monitoring Techniques 31

6. Recommendations on Considering Soil Carbon for the Forest Protocol 35

   a. Assessment of general magnitude of potential disturbance associated with pre-, during- and post-harvest management activities 35

   b. Assessment of uncertainty in measurements and observations 37

   c. Summary of known effects of forest management for consideration by the Reserve 38

Bibliography 40

Appendix 1: Distribution of four main soil types in the United States 45

Executive Summary

Soil carbon accounts for 50-75% of all forest carbon in temperate and boreal regions, so small changes in soil carbon can have significant influence on total ecosystem carbon storage. The Climate Action Reserve has heretofore assumed no major effects of management activities on soil carbon stocks if management activities do not include mechanical site disturbance of more than 25% or disturbance on contours. This white paper shows that forest management activities have the potential to significantly increase or decrease soil carbon, although direct quantitative monitoring remains elusive. The following bullets summarize key results:

- There is a high amount of uncertainty regarding soil carbon dynamics in response to forest management since the results greatly depend on the dominant tree species, harvest type, soil type, site preparation techniques, time after disturbance, and multiple other factors. In many cases, the uncertainty associated with the effects of particular management techniques is large, and different studies offer conflicting information. This is largely due to the very heterogeneous spatial and temporal dynamics of soil carbon, and due to the fact that our understanding of belowground carbon processes is significantly weaker than our understanding of aboveground processes.

- Changes in site fertility, which result from different management techniques such as thinning or competing vegetation control, have the potential to increase soil carbon anywhere between 20-40%, especially on poor soils. This is due to increases in plant productivity, and, consequently, belowground carbon transport, as well as decreases in decomposition of recalcitrant soil carbon. This result may be offset by a stimulation of decomposition of labile carbon in the soil, as is the case in soils with high fertility/high amounts of labile carbon, but overall the effect is an increase in carbon stocks. These results depend on leaving the plant residues onsite, as removal of this biomass results in changes to the soil microclimate and stimulates soil organic matter decomposition. Studies indicate that leaving residues on-site has an overall positive effect on soil carbon stocks in conifer-dominated ecosystems, and results in carbon losses in broadleaf ecosystems, due to the relatively high contents of labile carbon in broadleaf versus conifer residues. Additionally, presence of nitrogen fixing shrubs promotes significant (20 % or more) gains in soil carbon, and should be encouraged.

- High disturbance site preparation activities, such as plowing, deep ripping, etc. will have significant negative effects on soil carbon, with potential losses as high as 30%, and should be avoided. Minimizing such disturbance, both in area and intensity, will ensure reduced losses of soil carbon. Recognizing this point, the guidelines within the new CDM Afforestation/Reforestation protocol stipulate a 10% area disturbance threshold for such activities.

- The type of tree harvest plays a significant role in soil carbon dynamics. Almost universally, whole tree harvests reduce soil carbon amount, by as much as 20%, while sawlog (bole only) harvests that leave residues such as bark, branches, etc. on site result in no significant losses, or in some cases gains in soil carbon of as much as 40%. Projects that include whole-tree harvesting will result in soil carbon losses that are significant compared to the total net carbon sequestered by a forest project.

- Rotation length is an important determinant of soil carbon gains/losses in the vast majority of examined systems, and appears to be a more important factor than harvest intensity. Available research shows that soil carbon lost during harvest activities is recovered in some systems within 50 years, but the interval is longer for more northern, less productive systems, and can be more than 100 years in some cases. This effect is dependent on soil type, with some soils experiencing greater losses than others. Since initial losses from harvest activities can be as high as 20% of ecosystem carbon, an interharvest period of adequate length is critical for ensuring that such losses are replenished.

- Thinning is an allowed management technique under the current Forest Protocol. Available evidence suggests that thinning results in changes to the soil microclimate, stimulating soil organic matter decomposition, and in some cases results in losses of inputs due to removal of biomass from the site. These effects are mitigated through increased tree productivity in the medium term (10 years), so ensuring appropriately long intervals between thinning treatments, and ensuring that biomass residues are left onsite is critical in order to minimize soil carbon losses.

- Soil carbon monitoring techniques are either imprecise or very expensive and time consuming. In order to assess the potential of soil carbon losses due to different management techniques, the Climate Action Reserve could consider adopting one of several models for estimating soil carbon dynamics, and modifying it based on most recent scientific literature. This will allow evaluation of proposed projects for potential soil carbon losses, as well as estimate the magnitude of such losses or gains.

Acknowledgements

Ecoshift Consulting would like to offer our sincere gratitude to Dr. Weixin Cheng (UCSC) and Dr. Mark Coleman (University of Idaho) for their help in ensuring the scientific integrity of this manuscript. We would also like to thank Rachel Tornek, Kathryn Bickel Goldman, John Nickerson, and Derik Broekhoff of the Climate Action Reserve for their invaluable comments on various drafts of this manuscript, and the Climate Reserve for the opportunity to contribute an important piece to the Forest Protocol.

List of Important Terms

Soil Horizons: The soil profile is divided by depth into several horizons. Below the forest floor, which consists of decomposing debris, lies the A horizon, or the surface horizon. Below the A horizon, in most soils, lie the E, B, and C horizons, in that order with increasing depth. The horizons are governed by different processes, including root dynamics, hydrology, and interaction between mineral and organic compounds. Generally, with increasing depth, the proportions of labile carbon decrease, and the proportions of recalcitrant carbon increase, although both fractions exist in all horizons.

Labile Carbon: Easily decomposable soil organic matter, including sugars and other light organic compounds. Commonly includes microbial biomass.

Recalcitrant carbon: Organic compounds that are more resistant to decomposition by microbes, primarily due to their complex chemical structure and a high C/N ratio. Characterized by long residence times in the soil.

Root Exudates: One of the primary modes of input of labile organic carbon into the soil. These are simple organic compounds that fine roots release into the surrounding soils, that tend to stimulate soil microbial activity, and release nutrients from soil organic matter.

Soil Fractions: Soil organic matter is not uniform, and is commonly broken up into multiple fractions, such as labile, and recalcitrant carbon, and sometimes includes medium-term carbon.

Carbon Deposition: Carbon deposition, in this context, refers to different processes that transfer carbon belowground, such as litterfall, microbial breakdown of organic matter, and root exudation.

Decomposition: Breakdown of organic compounds by soil microbes. Primarily dependent on temperature and moisture availability, as well as nitrogen availability. This is the primary mechanism of carbon loss from soils.

Dissolved organic carbon: Complex carbon compounds that are sometimes considered part of soil organic matter, but are easily transferred by water from surface to subsurface horizons, primarily responsible for transfer of organic compounds to the B horizon.

1. Introduction

The Climate Action Reserve (the Reserve) requested this white paper on soil carbon to better understand the effects of different forest management activities on soil carbon stocks. The current Reserve Forest Protocol does not require soil carbon accounting unless site preparation activities include physical disturbance, such as contour modifications, or plowing, furrowing, or deep ripping on more than 25% of the surface. In general, soil carbon accounting is difficult for reasons outlined below, and the results of management activities on soil carbon are uncertain, so the existing protocol tends to neglect changes to soil carbon. One recent development in this area has been recognition of soil carbon importance within the Clean Development Mechanism of the Kyoto Protocol (CDM) Afforestation/Reforestation guidelines. These guidelines specify that, in order to ensure soil carbon stability, physical disturbance should not exceed 10% of the project area, woody debris from harvesting should be left on-site, and removal of existing vegetation as part of site preparation shall not constitute more than 10% of the project area, with some caveats for traditional management[i].

Although the available knowledge base on effects of forest management on soil carbon stocks is significantly smaller than that of impacts of forest management on aboveground stocks, current Reserve Forest Protocol assumptions assume greater stability of soil carbon stocks than available data show. Therefore, there may be grounds for evaluating the effects of forest management activities on soil carbon stocks, and modifying project guidelines to exclude practices that result in significant, lasting losses of soil carbon.

The effects of different Forest Protocol project types on soil carbon will be varied and different potential sources of soil carbon loss will be important for each; the analysis in this document addresses effects of each project type. Current guidelines for Reforestation scenarios include standards on site preparation, rotation length, and harvest regimes. Sections 3, 4, and 5 of this document describe some potentially important effects of these factors on soil carbon dynamics, and show that some management techniques have significant potential for soil carbon reductions. Improved Forest Management projects specifically allow for actions such as competing vegetation control (brush removal), stand thinning, and increasing rotation lengths. These practices can, likewise, have a significant effect on soil carbon dynamics, and are highlighted in sections 3 and 4 of this document. Likewise, since Avoided Conversion projects

[i] http://cdm.unfccc.int/methodologies/ARmethodologies/tools/ar-am-tool-06-v1.pdf

allow tree planting and harvesting, and therefore site preparation activities, some important considerations for soil carbon are examined in subsequent sections.

The effects of forest management on soil carbon dynamics are varied both in terms of magnitude of impact and the timing of impact. As discussed below, although some practices result in significant changes in soil carbon, these changes may be mitigated over time, and their significance reduced, barring any further disturbance over time. This highlights the fact that it is critically important to consider time between disturbances to obtain an accurate picture of soil carbon dynamics, since multiple processes in an intact ecosystem affect soil carbon storage, and with time will mitigate effects of disturbance. The effects of time are not uniform in every instance because rates of input vary between different ecosystems and soil carbon exists in multiple forms. Some forms of soil carbon are more sensitive to both disturbance and recent inputs (labile carbon), while others take a much longer time to replenish (recalcitrant carbon). We discuss some of these details in the subsections below, and they are important to keep in mind throughout the discussion.

A. Basic Factors Affecting Soil Carbon Dynamics

Globally, soils constitute the largest terrestrial carbon pool, containing as much as 2,344 gigatons of carbon (Gt C) to the depth of 3 meters (Jobbagy *et al.*, 2000). This is more than three times the total carbon found in all forest biomass. Forest soils in particular contain more than double the amount of carbon found in forest biomass (Solomon *et al.*, 2007). However, current scientific understanding of soil carbon dynamics is considerably weaker than that of biomass carbon dynamics, primarily due to the difficulty of investigation. This contributes to large uncertainty in soil carbon sequestration potentials, leaving policy-makers unsure how to include soil carbon in climate policy and reluctant to include soil carbon sequestration as an acceptable offset. For example, it is unlikely that soil carbon sequestration will be included in provisions for Reduced Emissions from Deforestation and Degradation in the pending international climate agreement due to methodological complexity and a lack of baseline data (Pagiola *et al.*, 2009).

Soil carbon exists in several distinct pools, called fractions, with the shortest-lived carbon (<1 year old) represented by microbial biomass and labile root exudates, which are easily decomposable simple organic compounds released by roots into soil. Medium-term carbon, several years to decades old, is represented by more complex organic materials. Ancient carbon, hundreds to thousands of years old, is represented by humins and humic acids, among other materials. These pools are distinct from forest floor carbon, which consists of organic material on the soil surface and is not typically included in the accepted conception of soil carbon.

The impact of forest carbon project activities on soil carbon relates specifically to how management activities influence the net balance of carbon inputs and losses. To begin this analysis, understanding the processes by which carbon enters and exits the soil carbon pool is critical. There are two main processes by which carbon enters the soil pool, and one primary process for soil carbon loss. Carbon can either enter the soil through litterfall (decomposing woody and leafy material); a result of natural deposition or management activities where it is incorporated directly into mineral soil horizons or indirectly by way of surface organic matter, or it can enter the soil pool through rhizosphere processes, which include fine root death and root exudation[ii]. Carbon is lost through microbial decomposition, which is largely dependent on temperature, moisture, and substrate availability (Gershenson *et al.*, 2009).

A complex set of factors can affect soil carbon dynamics within forest management activities (Figure 1), which is why gaining the level of certainty required for Reserve's Forest Protocol is difficult. Forest management affects carbon gains and losses by changing the level of inputs to the soil carbon pool. This can include decisions to leave or remove organic material on-site after harvest and thinning (both of which also change N dynamics) as well as increasing rates of deposition through increased productivity and varying harvesting regimes. Likewise, forest management can affect soil carbon dynamics by changing rates of microbial decomposition, changing environmental conditions such as temperature and moisture, and changing the quality of litter inputs (more labile versus more recalcitrant inputs). Another important factor in decomposition of carbon in the context of forest management is the stabilization of charcoal carbon, which is a common input in managed forests following harvest. Charcoal is created through the incomplete combustion of organic material, which is resistant to microbial decomposition. If charcoal is incorporated into soils, it can serve as an important long-term soil carbon pool, as well as increase overall soil quality (Lehmann, 2007, Kuzyakov *et al.*, 2009). In addition, site preparation activities frequently include burning of slash and other debris left over from harvest, and these inputs can have a potentially significant influence on stability of soil

---

[ii] Root exudation is a process of releasing labile carbon from living fine roots, which results in carbon inputs to the soils and stimulation of soil microbial decomposition, called priming.

organic matter. Another issue is that soil carbon is sensitive to soil type, as higher clay content increases amounts of carbon adsorbed to soil surfaces, and soil structural characteristics, such as soil aggregation, which provides physical protection from decomposition for soil organic matter. And finally, fertilization has been shown to affect soil carbon stocks, increasing them by as much as 25% (Heath *et al.*, 2003). Combined, these activities can affect soil carbon in multiple, interrelated, and competing ways, and given that the state of scientific knowledge on the topic is far from complete, clear, generalizable conclusions on the effects of any single activity are often not available. In this white paper we have attempted to summarize and draw conclusions on this highly complex topic.

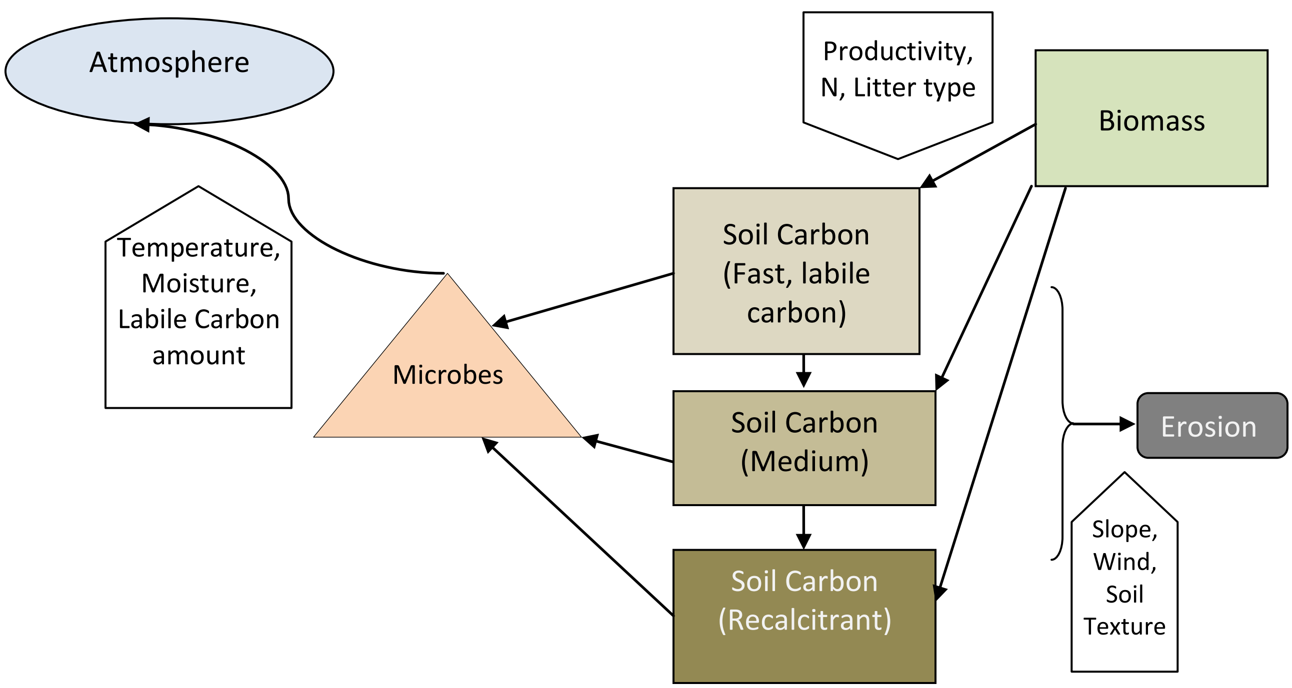


Figure 1. Basic Forest Soil Carbon Cycle:

Thin arrows indicate flows of carbon, thick arrows indicate main regulating factors, and different shapes indicate different carbon pools.

B. Soil carbon sequestration issues in forests: Projections for overall sequestration potential

Multiple studies have projected significant sequestration potential in U.S. forest soils, with estimates for temperate forests as high as 4.8 t CO_2e/acre/year (Houghton *et al.*, 2001).

Overall, based on the productive area of U.S. temperate forests of 504 million acres, the total sequestration potential for forests overall has been estimated at 176.2 to 681.9 Mt CO_2e /year, with an average of 388.7 Mt CO_2e /year (Heath *et al.*, 2003). Woodbury et al. (2007) arrived at slightly higher estimates by including forest products, and estimated that between 1990 and 2005 U.S. forests and the wood products sector sequestered an average of 594.54 Mt CO_2e /year. Although soil carbon stocks accounted for 48% of all forest carbon, they contributed only 2% of overall sequestration, so the vast majority of sequestration potential is due to increases in biomass carbon. This suggests that overall the soil carbon pool is relatively stable, although the apparent lack of change could be an additive result of some losses and some gains across the U.S. Additionally, studies from artificially CO_2-enriched forests show that there is no real potential of soil carbon sequestration due to increases in CO_2 because higher inputs will be offset by faster throughput of carbon in the soil system (Lichter *et al.*, 2005). Future potential depends on several factors, such as projected changes in precipitation and temperature changes, as well as fire frequency, species type, and management regimes. Thus, while, soil carbon sequestration is a small percent of overall forest carbon sequestration, it is still a sizable amount of carbon, and many variables can cause gains or losses in different system. The influence of these factors will be described in further detail in subsequent sections.

C. Uncertainty in Soil Carbon Science

The problem for accurate projections of changes in soil organic matter lies in the fact that our current understanding of soil organic matter dynamics is incomplete, and the exact influence of any given factor on soil organic carbon dynamics is poorly understood. Additionally, oftentimes exact recommendations are impossible due to the extreme spatial variability of soil carbon, both on micro and macro scales. Soil carbon amounts and types (labile versus recalcitrant) vary both horizontally and vertically throughout the soil profile, and can often be very different within a very small (sub-hectare) area. On macro scales (hundreds of miles) soil carbon is even more variable, as different microclimate, hydrological, and soil mineral conditions will result in widely variable soil carbon dynamics. Because soil carbon dynamics are influenced by multiple factors, and these factors affect soil carbon differently under different conditions, making unequivocal predictions is difficult if not impossible.

A few examples will serve to demonstrate the inherent complexity in soil carbon science. For instance, although greater productivity aboveground almost always translates into higher soil carbon inputs, such input of fresh labile (easily decomposable) carbon has the potential of stimulating decomposition of older, recalcitrant (difficult to decompose) soil carbon (Cheng *et al.*, 2003, Fontaine *et al.*, 2007), thereby decreasing overall soil carbon stocks. In another example of the interrelatedness of factors affecting soil carbon, the overall trend in global soil carbon respiration rates has been an increase in respiration with increasing temperature; however, it is unclear if that trend is offset by higher inputs from higher productivity (Bond-Lamberty *et al.*, 2010). Although generally carbon is likely to be sequestered in lands converted from agriculture to forests and in existing forests in temperate zones (Post *et al.*, 2000), such as U.S. northeastern forests (Goulden *et al.*, 1996), quantification of soil carbon dynamics remain problematic. In some cases, variations in the composition of tundra plant communities has affected the amounts of carbon sequestered, and even contributed to overall carbon losses from such ecosystems (Kwon *et al.*, 2006), and such changes are expected to affect northern forests in general, as currently dominant plant species are negatively affected by changes in disease dynamics, precipitation, and temperature. Certain ecosystems can be highly problematic: in cases of high-elevation seasonally dry forests, net ecosystem carbon uptake is highly variable, and depends largely on precipitation amounts and timing (Monson *et al.*, 2002). Some complexities may trump all other factors: a recent model of global forest carbon dynamics has shown that global forests have the potential to become overall carbon sources after the year 2050, largely due to increases in soil respiration, as well as increases in fires due to drought (Cox *et al.*, 2000). These effects could be a result of increased soil organic matter carbon fluxes, which have been suggested to result from the interaction of elevated CO_2 concentrations and elevated temperature (Butnor *et al.*, 2003, Tingey *et al.*, 2006). It is likely that increased soil fluxes from high latitude ecosystems will reduce soil carbon gains from sequestration through increased respiration rates (Luo *et al.*, 1996, Norby *et al.*, 2002, Bernhardt *et al.*, 2006).

These studies illustrate the significant uncertainty associated with long-term projections of soil carbon stability; even if some current management practices may have no effect, or a positive effect on soil carbon, climate change may negate these effects or change rates of carbon inputs or outputs in certain systems. However, overall, current research suggests that one of the most critical components to successful soil carbon retention in forests is proper management, which reduces some types of disturbance, while actively encouraging processes that protect soil organic carbon from decomposition through both chemical and physical means. We will discuss these techniques in sections 2-4.

D. Effect of site-specific factors, such as soil fertility and precipitation regimes on soil carbon

Availability of key factors, such as nutrients and water, as well as other site-specific factors such as forest species composition, litter layer characteristics, and temperature regimes all have the potential to affect soil carbon dynamics. Although these factors may seem outside the management regime, their effect on the variability and uncertainty of soil carbon gains and losses is such that they cannot be ignored. Since turnover time for soil carbon is largely determined by the rate of microbial decomposition, we must understand the effects of the above-mentioned factors on microbial dynamics.

One important factor, often overlooked when looking strictly at forest management practices, is changes in soil fertility. Most forests in the United States receive additional N inputs from fossil-fuel burning, even though the rates of N deposition are not the same in all forests and are a much more significant concern in Eastern forests. Although the Reserve Forest Protocol does not allow direct broadcast fertilization, experiments simulating N deposition allow us a better understanding of the effects of increased N deposition on soil carbon dynamics, which may interact with other changes caused by management practices.

The magnitude and lack of uniformity in effects makes N deposition an important concern. A study in an oak-dominated forest and a sugar maple system has found that, while N fertilization resulted in a 10% gain in soil carbon in an oak-dominated forest with low litter accumulation levels, it resulted in a 20% loss of soil carbon in the sugar maple system with high litter accumulation levels (Waldrop *et al.*, 2004). This can partly be explained by findings that show that N availability enhances decomposition of labile carbon pools, while simultaneously stabilizing more recalcitrant soil carbon (Neff *et al.*, 2002). Since atmospheric N deposition is projected to increase following increased rates of fossil fuel burning, and some forest practices result in increased N availability (aside from direct broadcast fertilization, which is not allowed under Reserve protocols), the understanding of the interactions between site-specific conditions and N deposition levels is critical for assessments of potential soil carbon gains and losses.

Specifically, the location of a particular project can influence the potential of different management practices to affect soil carbon (i.e. a project in a heavy nitrogen deposition area that is dominated by forests with a high organic matter content and litter accumulation will have substantial (up to 20%) loss of soil carbon, and therefore up to a 10% loss of total forest carbon).

Another major factor that is projected to change with changing global climatic conditions is the overall amount and the timing of precipitation in different parts of the U.S. Climatic changes are not projected to be uniform; some areas will have major precipitation changes, while others will not, and temperature is projected to change differently in different areas. For instance, in the Sierra Nevada precipitation amount and timing is projected to change drastically, which will affect soil carbon, while coastal California is not projected to experience major changes (Snyder *et al.*, 2002) . Unfortunately, regional climate models are in their infancy, so we don't have data for all of the US at a necessary spatial resolution.

As a result of a changing climate, soil microclimate will also change variably in different areas of the United States. Aside from affecting overall forest productivity and fire regimes, soil moisture also regulates belowground processes, including fine root growth (Gershenson *et al.*, In Revision) and microbial dynamics (Curiel Yuste *et al.*, 2007). In the broadest terms, higher soil moisture results in higher levels of microbial activity, which in turn results in higher carbon losses from soils. Although this relationship does not always hold, for instance in the case of drying waterlogged soils, decomposition is actually expected to increase (Davidson *et al.*, 2006). In general we can expect that areas that will face a decrease in precipitation will experience a reduction in soil respiration and vice-versa. Depending on the soil type, then, different management strategies will result in higher soil carbon retention. The difficulty in projecting the effects of changing precipitation and temperature lies in the inherent heterogeneity of current conditions, uncertainty regarding future changes, and uncertainty in the effects of these changes on different soils and different soil carbon stocks. Since soils and soil carbon are incredibly heterogeneous spatially on small and large scales, and carbon content and properties vary by depth, the responses to changes in climatic conditions will vary tremendously, and these variations are very poorly understood. It is one of the main challenges in examining soil carbon dynamics, and is an issue regardless of topic within soil carbon discussions. This problem will make it difficult to propose concrete universal solutions, since the direction and magnitude of effects are often unclear, or have only been described in a limited number of ecosystem or soil types.

These two issues highlight the complexity in determining changes in soil carbon stocks due to management practices. If factors outside the management regime can have a drastic effect on soil carbon stocks, it may be difficult to attribute sequestration or losses to any specific activity, and actual storage of carbon in soil may be very different that what is expected.

2. Effects of Pre-Harvest Management Techniques on Soil Carbon

Overall, the single most important forest management technique for increasing soil carbon content is conversion of pastureland to forests, or reforestation (Lal, 2004). However, the soil carbon gains in the case of reforestation depend on multiple factors, including previous land use, and dominant species type (Paul *et al.*, 2002). Additionally, the full benefits of reforestation do not become apparent until 20-30 years after planting, since soil carbon declines initially, the increase does not begin until several decades after planting, and the duration is dependent on tree species and soil type (Nave *et al.*, 2010). The amount of soil carbon gained during stand establishment and development depends, in large part, on the management of the stand between planting and harvest, as well as on climatic variables and species composition. We will discuss some evidence from studies that show effects of common forest management practices with regards to the effects on soil carbon.

A. Fertilization and Competing Vegetation Control

Fertilization of forest stands can either be a result of active management, enhanced atmospheric deposition due to fossil fuel burning, or the presence of nitrogen fixing plants. Although broadcast fertilization is not allowed under the current Reserve Forest Protocol, control of brush vegetation, as well as other management practices, can result in a release of nutrients to the soil, which has a similar effect to N fertilization. Generally any input of fresh litter will increase nitrogen inputs. Studies that utilize artificial fertilization as a treatment are important because they investigate the mechanism of management effects on soil carbon. The section reviews relevant studies and concludes with a summary of key information for Forest Protocol development.

Generally, increased nitrogen inputs almost universally result in increased plant primary production, due to the critical role that nitrogen plays in photosynthesis, and therefore results in increased carbon uptake by biomass. In terms of soil carbon, the relationship is less clear. This is due to competing effects of increased C deposition as a result of increased production on the one hand, and changes in the rates of microbial decomposition on the other, since nitrogen availability can often enhance soil carbon decomposition. Some evidence from laboratory incubations suggests that with additional N fertilization in Ponderosa pine we observe a significant increase in soil carbon (Haile-Mariam *et al.*, 2000), and N additions appear to stabilize overall soil carbon, and reduce decomposition (Swanston *et al.*, 2004). One of the main determinants of whether N additions will make a significant difference is initial N content, with N poor sites showing the greatest benefit of additional fertilization in regards to soil carbon additions (McCarthy *et al.*, 2010). As a rule, increased fertilization increases soil carbon content, by an average of 20% in all horizons, and on average 40% in the A horizon (the layer of soil just underneath the layer of organic litter on the surface), as evidenced from a meta-analysis of multiple studies in multiple biomes (Johnson *et al.*, 2001). This can be roughly translated to a 10-15% overall gain in whole ecosystem carbon, depending on the ecosystem type. Additionally, the presence of natural nitrogen fixing plants also enhances soil carbon stocks as much, if not more than fertilization, although the differences between the two are not statistically significant (Johnson *et al.*, 2001). However, with increasing changes in CO_2 concentrations and temperature, projecting the effect of N fertilization on soil carbon stocks is difficult and uncertain, since the relationships between increased N deposition and soil carbon dynamics under that scenario is unclear (Hyvönen *et al.*, 2007).

Although the exact relationship between fertilization and belowground carbon content is variable, control of competing vegetation on soil carbon must be considered. As one of the allowed practices under Section 2.1.2 of the Forest Protocol, and a generally common practice in young stands that is aimed at reducing competition with the commercial stock, competing vegetation control has the potential of significantly affecting soil carbon stocks. Such practices are commonly done through mechanical means or by the use of herbicides, with vegetation commonly left in place. In a single-species stand with controlled competing vegetation, the general trends point to an increase in soil carbon content with fertilization; however, if the competing vegetation consists of nitrogen-fixing shrubs, such as *Ceanothus* shrubs common in

Sierra Nevada plantations, the presence of such shrubs results in an increase in soil carbon that is equal or greater to fertilization (Johnson *et al.*, 2001).

Several studies give further information on the relationship between vegetation control and soil carbon. The exact nature of the fertilization versus competing vegetation removal was evaluated by McFarlane et al. (2009) in the Sierra Nevada forest plantations, and they have found that, although all sites responded positively to fertilization, with increases in forest floor and soil carbon of almost 50%, competing vegetation control only statistically significantly increased soil carbon in low fertility sites by 20%, indicating that competing vegetation may not be a factor in soil carbon dynamics in sites with average fertility. One important caveat to this research is that, in order to ensure that forest floor carbon is incorporated into the soil carbon pool; disturbance such as fire must be minimized. This suggests that, although in some cases competing vegetation control serves a dual purpose of reducing competition for the main tree species and fertilization of soil, these effects are only apparent in low fertility soils. A similar study in forest plantations of the southeastern United States showed slightly different results, with fertilization having no effect on soil carbon storage and understory elimination significantly decreasing (as much as 40% in the B horizon) overall carbon storage (Shan *et al.*, 2001). The key mechanisms for these effects are the overall reduction in fine root production due to understory elimination, and an increase in decomposition and production in fertilized plots. The authors note that overall, understory elimination increased total biomass and total soil carbon (forest floor and mineral soil carbon) storage combined by 4%, and fertilization increased total carbon storage by 6%, but the results were largely due to increases in biomass and forest floor carbon, with a reduction in mineral soil carbon storage. Once again, barring major disturbance, there is a possibility of incorporating the increased forest floor carbon into soil pools. These results may be explained by the difference in effects that N additions have on different soil carbon pools. Neff et al.(2002) found that, although long term N fertilization did not have a significant effect on total soil carbon in an alpine environment, such treatment inhibited the decomposition of older, more recalcitrant carbon, and enhanced the decomposition of intermediate-age and labile carbon fractions. Finally, a study from recently harvested Douglas Fir sites showed that, following herbicide-based competing vegetation control measures, microbial soil respiration increased, bulk soil respiration decreased, and overall soil carbon content did not change (Slesak *et al.*, 2010), which points to an effect similar to fertilization in cases of competing vegetation control.

Combining these results indicates that sites that receive large amounts of high quality litter, either from increases in productivity following fertilization or increases in litter inputs from controlling competing vegetation, will experience a net reduction in *labile* carbon stocks due to increased decomposition, which may be offset by a stabilization of *older carbon* and, in the case of low productivity sites, by greatly increased biomass production. This effect is largely governed by the initial conditions in soils, as low fertility, and low labile carbon soils have greater potential for soil carbon gain, whereas high fertility and high labile carbon soils can lose overall soil carbon due to increased decomposition of labile carbon stocks. Since the potential for gains (as much as 20% of soil carbon, and therefore 10-15% of total ecosystem carbon in low fertility sites, Sierra Nevada) or losses (30-40% of soil carbon, 15-25% of total ecosystem carbon in high soil organic matter sites, Georgia) in soil carbon are significant, practices such as competing vegetation control must be carefully evaluated for their effect on soil carbon. The difficulty lies in a general lack of multiple studies that test these effects, and in the wide variation of these effects depending on initial site conditions, as well as major ecosystem types.

Overall, practices that contribute fresh litter, and therefore increase nitrogen input, in high organic matter soils will likely significantly decrease soil carbon stocks, while increasing them in sites with organic matter poor soils. Additionally, presence of nitrogen fixing shrubs can have a large effect on soil carbon, with a majority of studies showing a significant (20-40% of soil carbon, 15-25% in total ecosystem carbon) increase, and some studies showing a 10-20% decrease in soil carbon stocks, which is, once again, attributed to a stimulation of microbial decomposition in sites with high initial soil carbon (Johnson *et al.*, 2001).

B. Mechanical thinning

Another forest management technique with potential to influence soil carbon dynamics is thinning, which is a practice allowed under the Reserve's Forest Project Protocol and includes removal of diseased or suppressed trees. The effects of thinning will depend on the intensity and frequency of treatments, which are generally aimed at maximizing aboveground forest health and growth. Thinning practices are generally aimed at biomass management but may not be ideal for soil carbon management.

Thinning changes the microclimate, increasing light penetration and, therefore, temperature, which stimulates microbial activity. Additionally, thinning will reduce the amount of plant carbon entering the soil carbon cycle through reduced litterfall and rhizodeposition. In a recent review of multiple studies, Jandl et al. (2007) found that thinning negatively affects forest floor carbon pools, as well as mineral soil carbon, although the latter depended on the level of disturbance and on the method of incorporation of residues from thinning.

There is considerable uncertainty associated with this general conclusion, as the amount of available data is minimal. Therefore, these results may not be strong enough to warrant general conclusions, and contradictory cases may exist. For instance, studies from the south eastern US actually report potentially significant increases in soil carbon 14 years following thinning (Selig *et al.*, 2008). Some researchers have found that, although there is a negative effect on the forest floor carbon pool, there is no significant decrease in mineral soil carbon in the short term, suggesting that effects of thinning on mineral soil carbon may take several rotations to manifest, due to a continual reduction of litter input (Skovsgaard *et al.*, 2006). A study on thinning in a Ponderosa pine stand has found that, although soil respiration did not significantly change 3 and 16 years after thinning treatments, overall fine root biomass was lower even after 16 years, and overall soil carbon went from being a slight sink of carbon to being a significant source (200 g $C/m^2/y$) with thinning (Campbell *et al.*, 2009).

These data are conflicting, largely due to significant differences in the intensity of treatments as well as other experimental factors. Since available data are sparse we rely on the overall understanding of effects of reduction of aboveground biomass on soil carbon in order to understand implications for forest carbon projects. Any reduction in aboveground biomass, especially if it coincides with removal of slash, will create conditions that are favorable to increases in soil respiration, and consequently losses of soil carbon. These include increases in temperature, reductions in moisture, and increased inputs of fresh labile carbon from root decomposition. Potential losses are as high as 185 tCO_2e/acre, which are not offset by gains in other forest carbon pools (Hager, 1988 in Jandl *et al.*, 2007). In the medium term (1-5 years) these effects will be reversed by the increased growth of remaining trees due to reduced competition from removed biomass. The soil carbon losses will be compensated by higher carbon deposition rates from increased aboveground productivity. However, if thinning practices are frequent, soil carbon losses will not be compensated in the interim periods.

Overall, the available data and scientific understanding suggest that if thinning is a part of the management regime, it should be done infrequently, with maximum amount of residue left on-site, which would serve to reduce the negative microclimate effects (higher temperature and lower moisture) on soil respiration. This would also enable some transfer of forest floor carbon into the mineral soil carbon pool.

C. Conclusions

Pre-harvest management has potential of affecting soil carbon stocks, and these effects are largely determined by soil attributes.

- Activities that contribute fresh litter to the forest floor, such as control of competing vegetation, will result in significant gains of up to 20% in soil carbon in initially poor fertility soils, but a 40-60% decrease in fertile, high carbon soils. Fertile soils, such as the ones in the southeastern United States, can lose significant amounts of carbon due to competing vegetation control activities, and practices that contribute fresh litter inputs should be avoided in high fertility soils

- Mechanical thinning changes the temperature and moisture conditions of the soil, stimulating microbial decomposition of soil organic matter and reducing soil carbon stocks. Although there is considerable variation in reported results, both in geographical scope and in examined treatments, such activities have a short-term negative effect on soil carbon stocks. Increased productivity of remaining trees has the potential of replenishing soil carbon lost due to thinning within approximately 5 years in the examined system. As long as such activities are infrequent, they will not have adverse long-term effects on soil carbon dynamics. Additionally, if post-thinning debris is left on-site, then the changes to soil microclimate are minimized and soil organic matter decomposition dynamics are less affected.

3. Effects of harvest management techniques on soil carbon: harvest techniques, rotation time, harvest retention levels and soil type

Forest stand harvest has great potential to disturb soil carbon. The studies available are widely varied, both in terms of ecosystems, harvest techniques, and chosen treatments. In addition, the described effects vary greatly, although several major review articles have attempted to synthesize available information (Johnson *et al.*, 2001, Jandl *et al.*, 2007, Nave *et al.*, 2010). Because the synthesis papers vary in topic, they come to different conclusions in some cases, although there are some unifying themes. In this section, we examine the major case studies, as well as the results gleaned from synthesis studies, in order to assess the major effects of different aspects of forest harvest on soil carbon.

Depending on the method and intensity of harvest, different direct effects on soil carbon are possible, including physical soil disturbance through the impact of skid trails, exposing mineral soil, and mixing of the forest floor organic material with mineral soil (Yanai *et al.*, 2003). Overall, physical disturbance to the soil surface can range from 39% to 99% of the surface area, depending on the intensity of harvest, the type of harvested material, and the species of trees harvested (Yanai *et al.*, 2003). As mentioned earlier, any physical disturbance to the soil is a problem for retaining soil carbon stocks, as it exposes protected soil carbon to rapid decomposition resulting from exposure to oxygen, breaking apart soil aggregates, and increasing soil temperature, all of which stimulate soil microbial activity. Additionally, physical disturbance of soils on slopes has the potential for soil erosion, and thus further losses of carbon from the site.

A. Harvesting Techniques

Johnson and Curtis (2001) conducted a meta analysis of 73 studies of effects of different harvesting techniques on soil carbon and found that, overall, there was no significant effect of harvest on soil C dynamics (Figure 2, top open circle). This result is based on averaging the effects of reported studies and is not very useful for policy recommendations, as it includes widely different studies with different harvesting techniques and in different biomes. However, when they analyzed the effects of different types of harvest in different types of forests, a more complex picture emerged with important, significant results. Overall, the results of the majority of studies showed that, after harvest, ecosystems can experience anywhere between 30% soil carbon loss and a 60% soil carbon gain, which roughly translates to a 15-20% ecosystem carbon loss to a 30-40% ecosystem carbon gain. Most of these studies examined soil carbon dynamics within a few years after harvest; however, since treatments varied significantly between studies, it is difficult to draw more direct conclusions from this meta analysis, except to say that highly variable effects are possible. When the results are separated by harvesting technique, it becomes evident that whole-tree harvesting (removal of bole, top, and branches from the site) has a significant negative effect on soil carbon, and sawlog harvesting (removal of bole only, while leaving branches on-site) results in an overall increase in soil carbon.

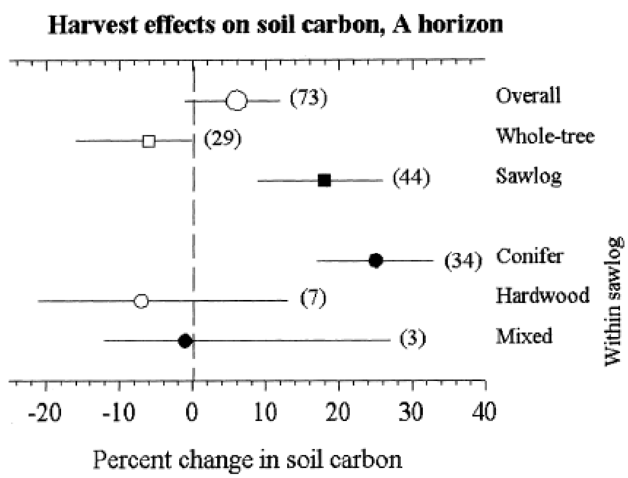


Figure 2. A cumulative result of a meta-study of 73 individual experiments examining the effects of forest harvesting on soil carbon, adapted from Johnson and Curtis, 2001

The cases of whole-tree harvesting showed a decrease in overall soil carbon after harvest events (Figure 2, open square), while sawlog harvesting of conifers showed a significant increase (Figure 2, top solid circle), and sawlog harvesting of hardwood and mixed forests showed no significant changes in soil carbon (Figure 2, bottom filled circle; graph represents mean values and 99% confidence intervals, and the numbers in parentheses reflect number of studies used to obtain these results).

The other major factor for net carbon uptake after harvest is the dominant tree species and their life history traits. Hyvönen et al. (2007) report that 1 year after coppicing total photosynthetic uptake of the regrowing shoots of a Turkish oak counterbalances ecosystem respiration (which is dominated by soil respiration and therefore soil carbon losses), while a clear-cut of Scots pine takes 20 years to regain its carbon sink status. This result implies that, depending on tree species, the amount of carbon available for belowground deposition differs drastically, and soil carbon may take a long time to recover from a disturbance depending on the overall ecosystem characteristics. Although results will vary depending on the ecosystem and harvested species, harvest methods appear to play a major role in soil carbon retention. There are some studies from different systems that illustrate the heterogeneity of these overall effects. A study in several sites in Sweden showed no discernible effect of types of harvest (whole tree versus sawlog) on soil carbon (Olsson *et al.*, 1996), but a similar study found that there were short-term changes in soil carbon, although long term changes (15 years) were not detected (Johnson *et al.*, 2002). Data from boreal forests in Canada suggest that conventional harvesting techniques that result in removal of stems but not branches and needles from the harvest site result in loss of soil carbon compared to non-harvested sites, but a greater retention of soil carbon when compared to whole-tree harvested forests, although the relationship depends on site characteristics (Peng *et al.*, 2002).

Overall, trends point to the importance of retaining biomass at harvest sites and focusing on sawlog, or bole harvesting, as opposed to whole tree harvests. The overall weight of evidence from the Johnson et al. (2001) review points to the importance of retaining residues on site; however, there are some studies that disagree with this conclusion.

B. Harvest Intensity

There are conflicting results on the effect of harvest intensity on soil carbon. The spectrum of harvest intensity treatments in the literature is very broad, but in general most treatments compare clear-cutting treatments with some type of selective cutting, either based on the number of stems per hectare or based on the size of trees being removed. Overall, the effect of reducing harvest intensity from clear-cutting to partial cutting is a net increase in soil carbon (Heath *et al.*, 2003), but the relationship is complicated, because there is a wide range of studies that oftentimes appear to disagree with each other.

The following review of relevant literature elucidates the relationship between harvest intensity and soil carbon. An evaluation of different intensities of harvest in Northern Wisconsin found that there was an increasing negative effect on soil carbon with increasing harvest intensity, and that surface soil carbon contents were significantly affected by removal of only the largest trees, based on diameter at breast height (Strong, 1997). However, a comparison of managed and unmanaged pine forests in Wyoming did not find a difference in soil carbon between the treatments, showing that harvest intensity had no effect on soil carbon (Chatterjee *et al.*, 2009b).

The most important factor for soil carbon content appears to be sampling time after harvest. In some cases, soil carbon stocks can remain the same immediately after harvest, as found in a study from a Norway spruce forest in Finland (Finér *et al.*, 2003). Yet a review of multiple studies that examined temporal dynamics after harvest reports that initially, soil carbon declines almost universally regardless of harvest type, by as much as 40%. However, within 40-60 years, depending on the dominant tree species, there is a return to previous soil carbon levels, with higher productivity forests returning quicker than low-productivity northern forests and forests that are found on nutrient-poor soils (Yanai *et al.*, 2003). *These results suggest that systems with rotation lengths of less than 50 years are likely to become net sources of carbon.*

In some cases, especially in colder climates with slower stand maturation times, soil carbon continues to decline after a clear-cut, probably because fresh inputs do not compensate for increased decomposition. In these cases, stands will regain the original carbon in timescales of hundreds of years (Liski *et al.*, 1998). The interesting part of this dynamic is that immediately after harvest soil carbon levels vary tremendously, and may in fact increase (which is commonly attributed to different post-harvest practices, further discussed in Section 4). Some studies report that soil carbon amounts do not significantly change after a clear-cut (Davis *et al.*, 2009); however, significant carbon losses are observed from soils during the establishment of new forest after a clear-cut, which is likely driven by both changes in microclimate and the enhanced decomposition of soil organic matter driven by priming[iii] (Diochon *et al.*, 2009).

Data from a recent meta-study helps explain the variation in trends observed in individual studies. The meta-study used results from 186 data sets to identify factors that determine the response of soil organic matter to forest harvesting (Nave *et al.*, 2010). Three important conclusions can be gleaned from the Nave et al. study. First, of all soil carbon pools, carbon losses are greatest in surface horizons, and effects decrease with increasing depth, as the percentage of more labile carbon decreases. Second, they also found, like Johnson et al. (2001),

[iii] Soil organic matter priming effect is the enhancement of soil organic matter decomposition due to the effects that inputs of labile carbon have on soil microbes stimulated by inputs of post-harvest litter and new root growth of the developing forest stand

that conifer-dominated systems exhibit smaller losses in soil carbon, likely due to the slower decomposition dynamics and higher C/N ratios of conifer residues. Third, and perhaps most critical, the most important factor determining potential soil carbon losses following harvest was soil type. U.S. forests primarily grow on four soil orders: Inceptisols, Ultisols, Spodosols, and Alfisols (See Appendix 1 for maps), and those harvested on Inceptisols and Ultisols lost 13% and 7% of soil carbon respectively (Figure 3), while soil carbon in the latter two was not significantly affected (Nave *et al.*, 2010). This effect was independent of all other factors, such as harvest type, tree species type, etc., although other effects were also noted, such as apparent higher losses of soil carbon in broadleaf-dominated forests than coniferous forests, due largely to the more labile nature of broadleaf residues. The authors also note that the losses observed in Inceptisols are important in the medium term, and that soil carbon amounts returned to pre-harvest levels within 20 years.

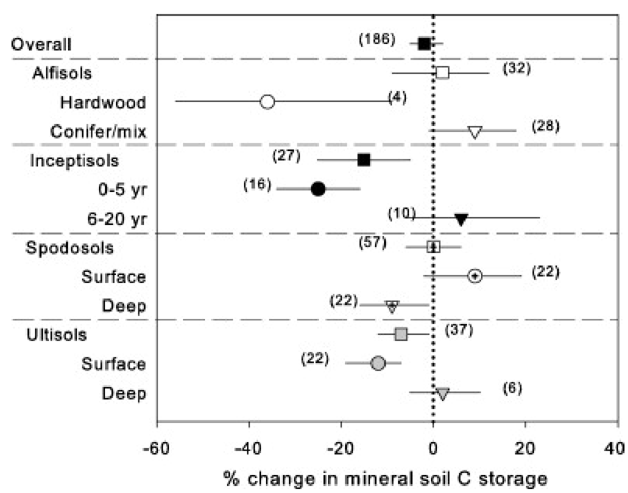


Figure 3. Changes in mineral soil carbon after harvest depending on dominant soil order, adapted from Nave et al. (2010). Changes where error bars cross over the 0% line are not statistically significantly different than 0, signifying no statistical difference but illustrating general trends.

C. Rotation Length

Multiple studies suggest that rotation length, rather than harvest intensity, is the major factor driving the effects of harvesting practices on soil carbon. One of the earliest studies, conducted in the Hubbard Brook forest, suggests that different types of harvest had a similar effect, and the length of the rotation determined whether the system overall lost soil carbon. One critical drawback to this study was that it focused on forest floor carbon and fine root biomass, rather than soil carbon specifically (Aber *et al.*, 1978). Although these results are not directly applicable to soil carbon dynamics, since these two pools are the main contributors to soil carbon, a reduction in both of these pools will dictate a reduction in soil carbon. In addition, this study does not project returns to pre-harvest levels in forest floor carbon and fine root biomass until 20-30 years after harvest. Seely et al. (2002), whose conclusions concur with the above, analyzed the effect of rotation length on soil carbon in multiple tree species and found that in all cases longer rotation lengths had a positive effect on overall soil carbon, and that soil carbon accumulation was most likely expected in rotations over 50 years for aspen and pine, and over 100 years for spruce, a species with much slower stand development. They also found that intervals between rotations shorter than 50 years resulted in 10%-20% losses in soil carbon regardless of tree type.

Other studies available in the literature help understand the finer complexities of the dynamic between rotation length and soil carbon. The effects of different stand ages of beechwood on the recalcitrant fraction of soil organic matter appear minimal (Hedde *et al.*, 2008), so some of these changes in soil organic matter due to frequent harvests could be due to a reduction in faster cycling (labile) carbon in soils. In boreal systems, Peng et al. (2002) found that increasing rotation lengths significantly increased soil carbon pools by as much as 36-40% between 30 and 120 year rotations. They note, however, that the effect is most pronounced for stem-only harvests, and that the effect of increasing rotation lengths is variable based on site conditions, such as site fertility, with less fertile sites responding better to longer rotation times. Nave et al. (2010) found an effect of rotation length, but they also found that soil type significantly affects the magnitude of this effect, with the average recovery time (return of soil carbon to pre-harvest levels) in Spodosols approaching 80 years, while data from the other soil orders is inconclusive due to lack of long-term studies. In this study, soil carbon content varied in the first few years after harvest, and declined by anywhere between 20-80% for the next twenty in the Inceptisol, Alfisol, and Ultisol systems. It is important to point out that if there are subsequent harvests carried out before soil carbon content is allowed to return to pre-harvest levels, further losses of soil carbon are likely, and the return to pre-initial harvest levels will require an even longer time. Thus, shorter rotations can create a gradual decrease in soil carbon.

Below we present two theoretical illustrations of the effect of harvest time on soil organic matter (Figure 4). The first graph represents harvest time intervals that create sustainable soil carbon pools, and the second represents soil carbon dynamics under harvest regimes that do not allow for complete recovery of soil carbon between harvests. This time period depends on soil type, but is generally reported to be on the order of 50 years on average. In general, in all cases it is important to ensure that soil carbon returns to pre-harvest levels before a new harvest takes place.

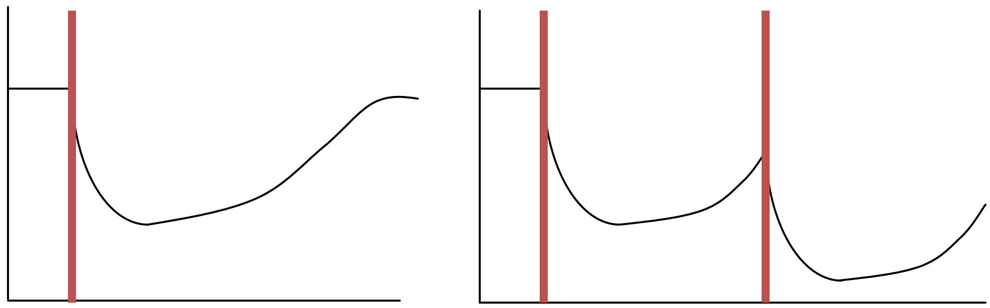


Figure 4. Theoretical soil carbon dynamics following harvest. Vertical red lines represent harvest events, x-axis represents time and y-axis represents soil carbon amount.

D. Conclusions

In general, trends on the effects of harvest management on soil carbon are difficult to discern, due to variation in responses across species, soil types, harvest types, and many other factors. However, three key conclusions arise from this review:

- Harvest activities have the potential to significantly change soil carbon stocks. Depending on the type of harvest, tree species, and the soils on which the forest is located, soil carbon stocks can experience anywhere from 40-60% declines to 20% gains, which will roughly translate to 20-40% ecosystem carbon losses to 10% ecosystem carbon gains. Soil carbon stocks are generally decreased by as much as 20% in cases of whole tree harvest, highlighting the importance of bole harvests for maintaining soil carbon stocks. This effect is especially pronounced in forests on Inceptisols (primarily found in the Pacific northwest, parts of the northeast, along the Appalachian mountains, and in Hawaii) and Ultisols (the predominant soil order in the southeast and south, and the northern Sierra Nevada in California). These are all regions with significant logging activity in the United States.

- Longer rotation periods help regain carbon lost during harvest, as do practices that reduce organic matter exports from harvest sites, such as whole-tree harvests. Available evidence suggests that rotation intervals that are less than 50 years may not be sufficient to replace soil carbon lost during prior harvests (which can be as much as 60% soil carbon, 30% ecosystem carbon for hardwood forests growing on Alfisols). Longer intervals, of at least 50 years, are likely to result, in most ecosystems, in replenishing soil carbon lost during prior harvests.

- Retaining non-bole biomass on site has multiple effects on soil carbon dynamics, from increasing the amount of potential forest floor carbon that can be incorporated into soil carbon later on to maintaining soil microclimate conducive to reduced decomposition. With the exception of a few studies, evidence suggests that stem-only harvests are more likely to result in retaining, and in some cases even increasing soil carbon, when compared to whole-tree harvests, although these results depend to a large extent on the fate of the residues left on site after harvest. The effects of post-harvest site treatment will be discussed in section 4.

4. Effects of Post-Harvest Management Techniques on Soil Carbon

Post harvest management has an important role to play in mitigating some of the potential soil carbon losses documented in section 3. One of the main considerations is management of post-logging debris, including the effects of incorporation of different litter on soil carbon dynamics. The most important changes that occur immediately after harvest, aside from large quantities of biomass removal, are microclimate changes and physical disturbance to soils, which can alter microbial decomposition dynamics, dissolved organic carbon leaching, and soil erosion rates. Losses of carbon to soil erosion are difficult to quantify, largely due to experimental difficulties, since tracing soils lost from sites through wind or water erosion is difficult. Erosion losses are most often associated with overall mechanical disturbance of the logging site.

A. Physical Disturbance

One of the results of harvest operations is mechanical disturbance to the forest floor, which acts on soil carbon in various ways, with some researchers reporting anywhere from 24% (Huntington *et al.*, 1990) to as much as 92% of the forest floor disturbed as a result of harvest operations (Martin, 1988). Some of this disturbance is an intentional part of site preparation, such as disking or plowing, and results in significant losses (over 20% of soil carbon, 10-15% of total ecosystem carbon) (Schmidt *et al.*, 1996).

Few studies exist that examine the direct effect of plowing on soil carbon in forests, but data from agricultural systems show that plowing has an immediate negative effect on soil carbon, with losses from only a few years amounting to 30% of the total carbon pool, and restoration studies have shown that, without intensive management, this carbon is difficult to get back (Ammann *et al.*, 2007). Some of this disturbance is incidental to harvest operations, and is a result of the use of heavy machinery, which disturbs the forest floor and often results in mixing the top soil horizons. Such high levels of disturbance break up the forest floor carbon layer and incorporate it into mineral soil, as well as expose mineral soil to the atmosphere, causing carbon to be oxidized and emitted as CO_2. In addition, hydrologic processes can cause carbon to be lost through erosion, and physically re-arrange the forest floor and mineral soil, increasing the difficulty of tracking carbon losses (Black *et al.*, 1995). Analyzing factors that affect erosion potential, Elliot et al. (1999) found that harvest intensity (whole tree versus bole and crown versus bole only) and soil compaction (a consequence of intensive use of heavy machinery) are the main factors in soil erosion potential, and that areas with steep slopes can lose significant amounts of soil, and therefore soil carbon, due to erosion. Although erosion may not be equivalent to complete carbon loss, carbon is removed from a particular site, and is either re-deposited elsewhere or is oxidized and respired by microbes due to the increased exposure of the surface area to oxygen. Prohibiting contour modifications in forest management will ensure a minimization of erosion losses, as the danger from soil erosion on level ground is minimal.

B. Dissolved Organic Carbon

Another immediate consequence of harvest is increased loss of carbon from the surface horizons in the form of dissolved organic carbon. Exposure of mineral soils and fresh residues to water, as well as root exudation and presence of severed root systems increase the chances of leaching of carbon from the surface horizons. However, multiple studies in different biomes found that, although leaching of dissolved organic carbon compounds increased significantly following harvest, most if not all of the leachate was stabilized in the lower profiles, and therefore stayed in the system. This effectively redistributing carbon away from the surface (e.g. Qualls *et al.*, 2000, Piirainen *et al.*, 2002), although it is difficult to generalize leaching dynamics due to differences in reported results (Kalbitz *et al.*, 2000). Overall, then, dissolved organic carbon is not of utmost concern in post-harvest practices.

C. Post-logging Debris Management

Perhaps one of the most critical variables in post-harvest management and site preparation is the management of post-logging debris. Multiple researchers note that when post-logging debris remains onsite, soil carbon increases in the short term after harvest (e.g. Knoepp *et al.*, 1997). This can partially be explained by the incorporation of organic matter into the forest floor and mineral soil through mechanical means during harvest, when machinery is driven on-site for other purposes, as well as the abovementioned dissolved organic carbon dynamics. However, another important factor that enables this increase is the microclimate that debris creates for soil bacteria (Devine *et al.*, 2007). Despite this understanding of the overall dynamic, the relationship is not always clear, since after a decade of intensive observation of a site in North Carolina, Powers et al. (2005) found no effect on soil carbon at the surface in plots where logging debris was retained. These results were potentially explained by the overwhelming effect of new vegetation regrowth that could have overwhelmed any signal from logging debris retention. The likely mechanism for the potential beneficial effects of logging debris retention was explored by Slesak et al. (2010), when they examined the effects of varying debris retention rates on soil respiration and total soil organic carbon. They found that at high levels of debris retention (80%), both bulk soil and microbial respiration were lower, and soil carbon retention higher, than in medium (40%) and debris removal treatments, which they attribute to the reduction in soil temperature that results from such practices. They found a similar trend in soil carbon concentration, with significantly higher concentrations in the plots with greatest retention of logging debris (Slesak *et al.*, 2010). Soil carbon losses can be minimized where retention of post-logging debris on site is maximized.

D. Site Preparation

Typically, site preparation activities are undertaken in order to clear land for new seedlings and improve soil fertility in the case of clear cut harvests. Unfortunately, these activities can have negative effects on overall carbon storage, as removal of debris and fertility enhancements create conditions favorable to microbial decomposition of soil carbon, and increases microbial decomposition of soil organic matter.

Certain techniques, such as slash burning, can retain a large percentage of the slash carbon in the forest floor, as carbon in charcoal is more resistant to decomposition and is likely the primary reason for carbon accumulation following fire events (Kuzyakov *et al.*, 2009). However, the intensity of site preparation, and therefore disturbance to soils, is generally correlated with an increase in carbon losses (Jandl *et al.*, 2007), so the beneficial effects of converting biomass carbon into charcoal may be offset by the disturbance to the site.

As is the case with harvest intensity, overall effects of site preparation on soil carbon are more negative with higher manipulation of the site. Ensuring that logging debris is left in place, or at a minimum converted to charcoal, reducing the amount of soil disturbance and forest floor-mineral soil mixing through mechanical incorporation, and making efforts to ensure that overall microclimate conditions do not change possible will ensure that increases in microbial activity and soil carbon decomposition, as well as dissolved organic carbon leaching and soil erosion, will be minimized. Projects that involves plowing, deep ripping, or furrowing will result in soil carbon losses that may be mitigated by long-term (over 50 years) rotation schedules, but should be avoided as some soil carbon lost may take much longer to be recovered. Although some mechanical disturbance to the soil is inevitable as a result of harvest of site preparation activities, such disturbance should be minimized to ensure minimal soil carbon losses. The new CDM guidelines[iv] for soil carbon management specify that such disturbance shall not exceed 10% of the project area, which is an example of a conservative allowance for such disturbance, and will likely result in significantly smaller soil carbon losses.

5. Monitoring Techniques

As described above, soil carbon dynamics are complex, both in time, since some effects of management decisions may not be evident for decades, and space, due to inherent heterogeneity of soil carbon both on a landscape level and with depth. Another problem is that soil carbon monitoring is fundamentally unlike aboveground biomass monitoring in that soil sampling is destructive, and, due to soil heterogeneity, far more samples must be obtained per sampling interval than aboveground biomass measurements, and thus each time sampling has to occur at a different place (Palmer *et al.*, 2002). Another problem is that soil carbon in itself is heterogeneous, as it exists in multiple forms, some of which are readily decomposable, and therefore vary significantly with seasonal and climatic changes, and some of which is highly recalcitrant, and is unlikely to change with management. These challenges are only some of the reasons why soil carbon inventories are not common in management practice and changes in forest soil carbon stocks are largely ignored, or assumed to be negligible.

However, as discussed above, different management practices have the potential to affect soil carbon stocks, either in the short or long term, with potential changes of anywhere between 40-60% percent losses to 20% gain in some cases (Section 2, 3, 4). At the total ecosystem carbon level, losses of carbon can constitute 20-30% in the short term, and time for returning these stocks to pre-activity levels can often be over 50 years. Various accounting techniques could be used to help ensure that potential carbon losses or gains are included in overall forest carbon balances. In order to overcome methodological difficulties, some researchers have proposed modeling approaches that use assumptions regarding the effects of climate, region, and

[iv] http://cdm.unfccc.int/methodologies/ARmethodologies/tools/ar-am-tool-06-v1.pdf

management type on soil carbon stocks. Early efforts focused on developing regional rules for carbon stocks and carbon accumulation curves, based on established data on climate, growing season, and basic forest type (Birdsey, 1992). Later efforts have combined these with some data on disturbance effects of different forest management practices (Hoover *et al.*, 2000). The Hoover model uses aboveground inventory data, and then uses region and planatation type and management technique information to estimate soil and litter carbon dynamics. They make some simple assumptions with regards to the effects of region and treatment types, as well as the type of harvest. However, the basic rules of soil carbon dynamics used in these accounting methods do not take into account the full complexity of effects of management and contributing environmental factors on forest soil carbon dynamics, and do not take into account most recent research findings. Even these methods require an on-the-ground inventory of standing biomass, and yet provide only a rough guide for soil carbon estimation. The major benefit of these techniques for estimating soil carbon is their low cost. These methods, although imprecise, allow land managers to quickly estimate their existing soil carbon stocks, and if updated using the findings of several of the recent review papers discussed in sections 2-4 (e.g. Johnson *et al.*, 2001, Jandl *et al.*, 2007, Nave *et al.*, 2010), can provide a rapid, cost effective way to roughly estimate both existing soil carbon stocks and the potential impact of management decisions.

Currently, the Reserve Forest Protocol does not require soil carbon accounting in almost all cases, because it assumes that the changes in the soil carbon pool due to management activities are negligible, or that the amount of carbon in the soils returns to normal relatively quickly. While these assumptions are correct for certain types of activities, this review demonstrates that certain management activities can have a lasting effect on soil carbon. To account for such effects, the Reserve could employ one of these models as a tool for estimating soil carbon losses/gains, and ultimately could improve these models by updating them with new information reviewed above. This would allow an estimation of the potential of each project to affect soil carbon; however, the relative lack of precision of such estimates may not be sufficient for carbon accounting purposes of the Climate Action Reserve.

On the other end of the feasibility spectrum is a set of sophisticated techniques that allow for calculating both stocks and flows of carbon through the various parts of the ecosystem, including soil carbon, as well as calculations of changes of aboveground carbon fluxes. Using a combination of data from soil respiration measurements (losses of soil carbon due to microbial decomposition), destructive soil sampling for quantification of stocks, measurements of leaf-level photosynthesis for understanding of carbon uptake, and using the eddy-flux approach to measure total ecosystem carbon exchange (overall losses/gains of carbon from the ecosystem), a very precise estimate of all of these parameters can be made (e.g. Sanderman *et al.*, 2003, Misson *et al.*, 2006). The combination of these methods allows for a precise accounting of all ecosystem carbon flows, including soil carbon uptake and loss; however, they must be undertaken together in order to obtain an accurate picture of carbon dynamics. The main problem with such an approach is the immense cost associated with both the instrumentation and personnel time required for this approach. The costs of running such a monitoring program can easily reach hundreds of thousands of dollars per plot, and such programs are therefore unrealistic as a routine measurement technique for forest carbon offset projects. However, it may be useful to establish several test plots in different biomes in the United States in order to ground test any estimate protocols or modeling tool, as described earlier in the section.

A relatively recent suite of options for remotely determining soil carbon fluxes has been under development, based on using different spectral absorptions of carbon dioxide. Chatterjee et al. (2009a) review the different methodologies such as infrared reflectance spectroscopy and using inelastic neutron scattering for determining both soil respiration and carbon content. Unfortunately, such non-destructive measurements require expensive equipment (tens and, in some cases, hundreds of thousands of dollars) and constant calibration, and they require trained field personnel. Another option that has potential for certain stages of forest management is remote sensing using satellite observation. New sensors on satellites allow observation in different infrared spectrums, and these techniques have been used extensively to document carbon dioxide fluxes from forests (e.g. Garbulsky *et al.*, 2008). However, the critical problem for measurements of soil carbon fluxes is the need for direct observation of bare or near-bare soils by the satellite, which limits the use of remote sensing data for soil carbon fluxes to immediate post-harvest observation.

The last major suite of methods is also the most developed, and it involves direct measurements of soil carbon stocks through a variety of destructive sampling methods, most common of which is the dry combustion method, which allows for direct quantification of soil organic matter. The method itself is very simple and inexpensive; commercial soil testing labs can process each sample for under $10. The caveat lies in the necessity to collect a large number of samples in order to capture the spatial heterogeneity of soil organic matter (at least 20 soil cores, preferably performed at multiple depths, per plot), which is a very labor-intensive process, and concurrent sampling that is required (bulk soil porosity, moisture content, etc.) likewise requires significant time investment. The other problem is that the method does not allow for sufficient precision to detect small (<10%) changes in soil organic matter, due to the heterogeneity of soil carbon distribution, unless the number of samples is sufficiently large (Homann *et al.*, 2008), and site heterogeneity is the main factor in the number and timing of samples required to detect a difference.

Overall, there is no one ideal method for monitoring soil carbon stocks, and changes in those stocks, in forests. For practical reasons, a combination of direct sampling and modeling techniques may be required, with direct sampling used to establish the baseline soil carbon content, and modeling to predict changes in the soil carbon stocks due to management regimes. Repeated direct sampling may be required to verify model predictions, but the power of direct sampling to detect change rests on the amount of investment of time for sample collection.

6. Findings Relevant to Considering Soil Carbon for the Forest Protocol

A. Assessment of general magnitude of potential disturbance associated with pre-, during- and post-harvest management activities

As mentioned throughout the report, the magnitudes of potential carbon gains or losses associated with different forest management techniques is highly variable, and depend on multiple factors. Overall, soil carbon constitutes anywhere between 50-75% of the overall ecosystem carbon, making even small changes important in the context of the whole forest. The magnitudes of changes reported in the literature vary significantly, largely due to the inherent heterogeneity of soils, both within the soil profile and geographically, and making concrete recommendations in many cases is difficult. However, there are several management practices that have been shown to affect soil carbon.

Pre-harvest Activities

Forest stand management includes multiple activities that ensure the health of the commercial stand, reduce competition from non-commercial species, and improve soil fertility. We have highlighted multiple studies on the effects of fertilization on forest stands, even though direct fertilization is not allowed under Forest Protocol rules, because multiple activities increase nutrient inputs into soils. These include stand thinning, brush removal, encouraging nitrogen-fixing shrubs, and retaining woody and leafy debris on-site. Fertilization studies allow us to understand the effects of these added nutrients on soil carbon.

Although the effects of some pre-harvest activities on soil carbon are unclear, multiple studies have shown that activities that contribute fresh litter to the forest floor, such as control of competing vegetation, will result in significant gains of up to 20% in soil carbon in initially poor fertility soils, but a 40-60% decrease in fertile, high carbon soils. This effect is governed by the role that nitrogen inputs from fresh litter play in soil organic matter dynamics, where they stimulate decomposition of labile carbon, but stabilize more recalcitrant fractions. Additionally, in low fertility sites, such inputs stimulate above-ground production, which, in turn, results in higher levels of carbon deposition belowground. Fertile soils, such as the ones in the southeastern United States, can therefore lose significant amounts of carbon due to competing vegetation control activities. Mechanical thinning for disease and fire management, as well as removal of suppressed trees is a standard forestry practice, which is allowed under the current Forest Protocol. Removal of some trees within a stand allows greater growth and carbon fixation in remaining trees, and in many cases improves the health of the stand. However, thinning also changes the temperature and moisture conditions of the soil, stimulating microbial decomposition of soil organic matter and reducing soil carbon stocks. Exact estimates of the magnitude of losses are not readily available in the literature, as the types and frequencies of thinning vary greatly between studies. Regardless of the magnitude, studies report that the increased productivity of remaining trees has the potential of replenishing soil carbon lost due to thinning within approximately 5 years in the examined systems. Therefore, thinning will not have a significant effect on soil carbon in the cases where such activities are undertaken with low frequencies. Authors of multiple studies also note that if post-thinning debris is left on-site, then the changes to soil microclimate are minimized and soil organic matter decomposition dynamics are less affected.

Harvest Activities

Multiple studies have addressed the effects of harvest activities on soil carbon. Although on average harvest activities do not have a statistically significant effect on soil carbon, when we examine different systems and harvest techniques separately, several factors appear to have effects on soil carbon gains and losses in forest ecosystems. From the range of studies examined, we see that potential declines in soil carbon following harvest can be as high as 60%. Whole tree harvesting results in overall losses of soil carbon of as much as 20%, due to removal of all aboveground biomass from the site. In contrast, harvesting of saw-logs only results in an overall 30-40% gain in soil carbon, due to the subsequent incorporation and decomposition of harvest residues into soil organic pools. These effects presist for various periods of time, and are mitigated at different rates in different ecosystems. Typically, most losses are mitigated within 50 years from disturbance. Additionally, harvests of coniferous species result in overall soil carbon gains, whereas broadleaf species harvest effects on soil carbon are uncertain. The likely mechanism for this difference is the relative recalcitrant nature of conifer residues, when compared to broadleaf residues, which are more easily decomposable. Retaining harvest residues on site after harvest, in general, protects, and in some cases enhances soil carbon. A lot of the variation in these numbers is explained by the dominant soil type (order), and harvest activities on Inceptisols and Ultisols are likely to result in greater losses of soil carbon.

One of the critical variables in the effects of harvests on soil carbon is time. Soil carbon stocks generally recover with time after harvests, although the recovery time is greatly dependent on subsequent forest productivity. Recovery times vary anywhere between 25-100 years, and rotation times that are shorter than typical recovery times will result in lasting losses of soil carbon that are not compensated for. Longer rotation schedules, over 50 years, can ensure that no matter the magnitude of soil carbon loss, soil carbon stocks can recover before the next harvest.

Post-Harvest Activities

Management decisions after harvesting can have lasting implications on soil carbon stocks. Current Reserve rules for Forest Projects allow up to 25% site disturbance with techniques such as plowing, deep ripping, or furrowing. Such practices result in significant losses of soil carbon (up to 30%), and the current standards may still result in significant carbon losses. In general, studies show that disturbance should be minimized, and that, as noted earlier, logging debris should be left on-site in order to minimize the changes in soil microbial activity that usually result from higher soil temperatures that are observed after harvest due to the lack of tree canopy cover.

B. Assessment of uncertainty in measurements and observations

As we discussed above, not only does considerable uncertainty exist when we consider the effects of different forest management practices on soil carbon, but there is a large discrepancy between studies in different biomes, on different soils, and between different management techniques. Additionally, available monitoring techniques often lack the spatial and temporal resolution to capture changes in soil organic matter pools, and the cost of monitoring is prohibitive for real-time measurements in forest offset projects. In addition, the overall body of knowledge of soil carbon dynamics is small, and does not cover the diversity of ecosystems in North America. This is due to the fact that soil carbon investigation techniques are relatively new, and novel methods are under development. We also lack a sufficient body of studies on longer-term effects on soil carbon, which presents a problem for estimating the timescales at which these effects are important. These factors pose a problem for making unequivocal recommendations, as the effects can be widely different, and depend on a multitude of factors. These caveats aside, although we may not have exact data on the effects of particular management techniques on soil carbon, the general direction of such effects has been described in this white paper. Updating existing models with current information should provide relatively accurate and cost effective ways of projecting such impacts.

C. Summary of known effects of forest management for consideration by the Reserve

Currently the Reserve Forest Protocol does not specify the type of pre-, during-, and post-harvesting techniques that would require soil carbon accounting in Forest Projects. The only requirement for such accounting is based on the degree of site disturbance due to plowing, deep ripping, or furrowing, or site preparation activities that occur on contours. The available body of knowledge shows that other activities have direct effects on soil carbon content.

- Forest management that includes (a) competing vegetation control, (b) thinning, or (c) other activities that alter canopy cover or organic matter inputs can have significant effects on soil carbon stocks in the long term, and should be infrequent enough to allow soil carbon stocks to return to original conditions. This is especially important on sites with high original organic matter content. Soil carbon losses should be considered if such activities are undertaken at time intervals shorter than 10 years, and/or if biomass residues are removed from the site.
- Presence of nitrogen-fixing shrubs, which occur following previous harvests, should be encouraged, as they contribute to significant increases in soil carbon.
- Results of multiple studies show that harvest plans that include removal of all residues will result in soil carbon losses, and should require an assessment of soil carbon stocks after harvest. This is particularly important on sites that are located on Inceptisols and Ultisols, as there is significant potential of losses of soil carbon from those types of soil (Appendix 1). Bole-only harvest should be encouraged, and projects that involve whole-tree harvesting should account for soil carbon losses.

- Likewise, projects with scheduled rotation intervals shorter than 50 years should demonstrate that forests have regained soil carbon lost during prior harvests. In boreal or low-productivity ecosystems (i.e. Scotts Pine –dominated systems) this interval should be at least 75 years, as the mitigation of soil carbon losses during harvest occurs at a slower rate.

- Post harvest activities that remove residual biomass from the site or involve physical disturbance (plowing, furrowing, deep ripping) to the soils over 10% of the project area should account for soil carbon losses, as these can be significant and long-lasting.

- Developing an updated model for soil carbon losses and gains from forest management activity can help in ensuring proper soil carbon accounting. This can be accomplished using the Hoover et al. (2000) model as a reference starting point, and including more recent data to improve accuracy in predictions.

Bibliography

Aber JD, Botkin DB, Melillo JM (1978) Predicting the effects of different harvesting regimes on forest floor dynamics in northern hardwoods. *Can. J. For. Res.*, **8,** 306-315.

Ammann C, Flechard CR, Leifeld J, Neftel A, Fuhrer J (2007) The carbon budget of newly established temperate grassland depends on management intensity. *Agriculture, Ecosystems & Environment,* **121,** 5-20.

Bernhardt ES, Barber JJ, Pippen JS, Taneva L, Andrews JA, Schlesinger WH (2006) Long-term effects of free air CO2 enrichment (FACE) on soil respiration. *Biogeochemistry,* **77,** 91-116.

Birdsey RA (1992) Carbon storage and accumulation in United States forest ecosystems. In *Gen. Tech. Rep. WO-59*. U.S. Department of Agriculture, Forest Service, Washington Office, Washington, DC.

Black TA, Harden JW (1995) Effect of timber harvest on soil carbon storage at Blodgett Experimental Forest, California. *Can. J. For. Res.*, **25,** 1385-1396.

Bond-Lamberty B, Thomson A (2010) Temperature-associated increases in the global soil respiration record. *Nature,* **464,** 579-582.

Butnor JR, Johnsen KH, Oren RAM, Katul GG (2003) Reduction of forest floor respiration by fertilization on both carbon dioxide-enriched and reference 17-year-old loblolly pine stands. *Global Change Biology,* **9,** 849-861.

Campbell J, Alberti G, Martin J, Law BE (2009) Carbon dynamics of a ponderosa pine plantation following a thinning treatment in the northern Sierra Nevada. *Forest Ecology and Management,* **257,** 453-463.

Chatterjee A, Lal R, Wielopolski L, Martin MZ, Ebinger MH (2009a) Evaluation of Different Soil Carbon Determination Methods. *Critical Reviews in Plant Sciences,* **28,** 164 - 178.

Chatterjee A, Vance GF, Tinker DB (2009b) Carbon pools of managed and unmanaged stands of ponderosa and lodgepole pine forests in Wyoming. *Canadian Journal of Forest Research,* **39,** 1893-1900.

Cheng W, Johnson DW, Fu S (2003) Rhizosphere Effects on Decomposition: Controls of Plant Species, Phenology, and Fertilization. *Soil Sci Soc Am J,* **67,** 1418-1427.

Cox PM, Betts RA, Jones CD, Spall SA, Totterdell IJ (2000) Acceleration of global warming due to carbon-cycle feedbacks in a coupled climate model. *Nature,* **408,** 184-187.

Curiel Yuste J, Baldocchi DD, Gershenson A, Goldstein A, Misson L, Wong S (2007) Microbial soil respiration and its dependency on carbon inputs, soil temperature and moisture. *Global Change Biology,* **13** 2018 - 2035.

Davidson EA, Janssens IA (2006) Temperature sensitivity of soil carbon decomposition and feedbacks to climate change. *Nature,* **440,** 165-173.

Davis SC, Hessl AE, Scott CJ, Adams MB, Thomas RB (2009) Forest carbon sequestration changes in response to timber harvest. *Forest Ecology and Management,* **258,** 2101-2109.

Devine WD, Harrington CA (2007) Influence of harvest residues and vegetation on microsite soil and air temperatures in a young conifer plantation. *Agricultural and Forest Meteorology,* **145,** 125-138.

Diochon A, Kellman L, Beltrami H (2009) Looking deeper: An investigation of soil carbon losses following harvesting from a managed northeastern red spruce (Picea rubens Sarg.) forest chronosequence. *Forest Ecology and Management,* **257,** 413-420.

Elliot WJ, Page-Dumroese D, R. RP (1999) The effects of forest management on erosion and soil productivity. In *Soil Quality and Soil Erosion* (ed Lal R), pp. 195-208. CRC Press, Boca Raton, FL.

Finér L, Mannerkoski H, Piirainen S, Starr M (2003) Carbon and nitrogen pools in an old-growth, Norway spruce mixed forest in eastern Finland and changes associated with clear-cutting. *Forest Ecology and Management*, **174,** 51-63.

Fontaine S, Barot S, Barre P, Bdioui N, Mary B, Rumpel C (2007) Stability of organic carbon in deep soil layers controlled by fresh carbon supply. *Nature*, **450,** 277-280.

Garbulsky MF, PeÑUelas J, Papale D, Filella I (2008) Remote estimation of carbon dioxide uptake by a Mediterranean forest. *Global Change Biology*, **14,** 2860-2867.

Gershenson A, Bader NE, Cheng W (2009) Effects of substrate availability on the temperature sensitivity of soil organic matter decomposition. *Global Change Biology*, **15,** 176-183.

Gershenson A, Misson L, Tang JW, Curiel Yuste J, Goldstein A, Cheng W (In Revision) Climate effects on above and belowground phenological development in a young Ponderosa pine forest. *Ecology*.

Goulden ML, Munger JW, Fan S-M, Daube BC, Wofsy SC (1996) Measurements of carbon sequestration by long-term eddy covariance: methods and a critical evaluation of accuracy. *Global Change Biology*, **2,** 169-182.

Haile-Mariam S, Cheng W, Johnson DW, Ball JT, Paul EA (2000) Use of carbon-13 and carbon-14 to measure the effects of carbon dioxide and nitrogen fertilization on carbon dynamics in ponderosa pine. *SSSAJ*, **64,** 1984-1993.

Heath LS, Kimble JM, Birdsey RA, Lal R (2003) The potential of U.S. forest soils to sequester carbon. In *The potential of U.S. forest soils to sequester carbon and mitigate the greenhouse effect.* (eds Kimble JM, Heath LS, Birdsey RA, Lal R), pp. 385-394. CRC Press, Boca Raton, FL.

Hedde M, Aubert M, Decaëns T, Bureau F (2008) Dynamics of soil carbon in a beechwood chronosequence forest. *Forest Ecology and Management*, **255,** 193-202.

Homann PS, Bormann BT, Boyle JR, Darbyshire RL, Bigley R (2008) Soil C and N minimum detectable changes and treatment differences in a multi-treatment forest experiment. *Forest Ecology and Management*, **255,** 1724-1734.

Hoover CM, Birdsey RA, Heath LS, Stout SL (2000) How to Estimate Carbon Sequestration on Small Forest Tracts. *Journal of Forestry*, **98,** 13-19.

Houghton JT, Jenkins GJ, Ephraums JJ (Eds.) (2001) *IPCC Climate Change 2001: The Scientific Basis*, Cambridge University Press, New York.

Huntington TG, Ryan DF (1990) Whole-tree-harvesting effects on soil nitrogen and carbon. *Forest Ecology and Management*, **31,** 193-204.

Hyvönen R, Ågren GI, Linder S, *et al.* (2007) The likely impact of elevated [CO2], nitrogen deposition, increased temperature and management on carbon sequestration in temperate and boreal forest ecosystems: a literature review. *New Phytologist*, **173,** 463-480.

Jandl R, Lindner M, Vesterdal L, *et al.* (2007) How strongly can forest management influence soil carbon sequestration? *Geoderma*, **137,** 253-268.

Jobbagy EG, Jackson RB (2000) The Vertical Distribution of Soil Organic Carbon and its Relation to Climate and Vegetation. *Ecological Applications*, **10,** 423-436.

Johnson DW, Curtis PS (2001) Effects of forest management on soil C and N storage: meta analysis. *Forest Ecology and Management*, **140,** 227-238.

Kalbitz K, Solinger S, Park JH, Michalzik B, Matzner E (2000) Controls on the Dynamics of Dissolved Organic Matter in Soils: A Review. *Soil Science,* **165,** 277-304.

Knoepp JD, Swank WT (1997) Forest Management Effects on Surface Soil Carbon and Nitrogen. *Soil Science Society of America Journal,* **61,** 928-935.

Kuzyakov Y, Subbotina I, Chen H, Bogomolova I, Xu X (2009) Black carbon decomposition and incorporation into soil microbial biomass estimated by 14C labeling. *Soil Biology and Biochemistry,* **41,** 210-219.

Kwon HJ, Oechel WC, Zulueta RC, Hastings SJ (2006) Effects of climate variability on carbon sequestration among adjacent wet sedge tundra and moist tussock tundra ecosystems. *Journal of Geophysical Research-Biogeosciences*, **111**.

Lal R (2004) Soil Carbon Sequestration Impacts on Global Climate Change and Food Security. *Science,* **304,** 1623-1627.

Lehmann J (2007) A handful of carbon. *Nature,* **447,** 143-144.

Lichter J, Barron SH, Bevacqua CE, Finzi AC, Irving KF, Stemmler EA, Schlesinger WH (2005) SOIL CARBON SEQUESTRATION AND TURNOVER IN A PINE FOREST AFTER SIX YEARS OF ATMOSPHERIC CO2 ENRICHMENT. *Ecology,* **86,** 1835-1847.

Liski J, Ilvesniemi H, MÄKelÄ A, Starr M (1998) Model analysis of the effects of soil age, fires and harvesting on the carbon storage of boreal forest soils. *European Journal of Soil Science,* **49,** 407-416.

Luo Y, Jackson RB, Field CB, Mooney HA (1996) Elevated CO2 increases belowground respiration in California grasslands. *Oecologia,* **108,** 130-137.

Martin CW (1988) Soil Disturbance by Logging in New England--Review and Management Recommendations. *Northern Journal of Applied Forestry,* **5,** 30-34.

McCarthy HR, Oren R, Johnsen KH, *et al.* (2010) Re-assessment of plant carbon dynamics at the Duke free-air CO2 enrichment site: interactions of atmospheric [CO2] with nitrogen and water availability over stand development. *New Phytologist,* **185,** 514-528.

McFarlane KJ, Schoenholtz SH, Powers RF (2009) Plantation Management Intensity Affects Belowground Carbon and Nitrogen Storage in Northern California. *Soil Sci. Soc. Am. J.,* **73,** 1020-1032.

Misson L, Gershenson A, Tang J, Boniello R, McKay M, Cheng W, Goldstein A (2006) Influences of canopy photosynthesis and summer rain pulses on root dynamics and soil respiration in a young ponderosa pine forest. *Tree Physiology,* **26,** 833–844.

Monson RK, Turnipseed AA, Sparks JP, Harley PC, Scott-Denton LE, Sparks K, Huxman TE (2002) Carbon sequestration in a high-elevation, subalpine forest. *Global Change Biology,* **8,** 459-478.

Nave LE, Vance ED, Swanston CW, Curtis PS (2010) Harvest impacts on soil carbon storage in temperate forests. *Forest Ecology and Management,* **259,** 857-866.

Neff JC, Townsend AR, Gleixner G, Lehman SJ, Turnbull J, Bowman WD (2002) Variable effects of nitrogen additions on the stability and turnover of soil carbon. *Nature,* **419,** 915-917.

Norby RJ, Hanson PJ, O'Neill EG*, et al.* (2002) Net primary productivity of a CO2-enriched deciduous forest and the implications for carbon storage. *Ecological Applications,* **12,** 1261-1266.

Pagiola S, Bosquet B (2009). World Bank, Washington, DC.

Palmer CJ, Smith WD, Conkling BL (2002) Development of a protocol for monitoring status and trends in forest soil carbon at a national level. *Environmental Pollution,* **116,** S209-S219.

Paul KI, Polglase PJ, Nyakuengama JG, Khanna PK (2002) Change in soil carbon following afforestation. *Forest Ecology and Management,* **168,** 241-257.

Peng C, Jiang H, Apps MJ, Zhang Y (2002) Effects of harvesting regimes on carbon and nitrogen dynamics of boreal forests in central Canada: a process model simulation. *Ecological Modelling,* **155,** 177-189.

Piirainen S, Finér L, Mannerkoski H, Starr M (2002) Effects of forest clear-cutting on the carbon and nitrogen fluxes through podzolic soil horizons. *Plant and Soil,* **239,** 301-311.

Post WM, Kwon KC (2000) Soil carbon sequestration and land-use change: processes and potential. *Global Change Biology,* **6,** 317-327.

Powers RF, Andrew Scott D, Sanchez FG, Voldseth RA, Page-Dumroese D, Elioff JD, Stone DM (2005) The North American long-term soil productivity experiment: Findings from the first decade of research. *Forest Ecology and Management,* **220,** 31-50.

Qualls RG, Haines BL, Swank WT, Tyler SW (2000) Soluble organic and inorganic nutrient fluxes in clearcut and mature deciduous forests. *Soil Science Society of America Journal,* **64,** 1068-1077.

Sanderman J, Amundson RG, Baldocchi DD (2003) Application of eddy covariance measurements to the temperature dependence of soil organic matter mean residence time. *Global Biogeochemical Cycles,* **17,** 30.31-30.15.

Schmidt MG, Macdonald SE, Rothwell RL (1996) Impacts of harvesting and mechanical site preparation on soil chemical properties of mixed-wood boreal forest sites in Alberta. *Can. J. Soil Sci,* **76,** 531-540.

Seely B, Welham C, Kimmins H (2002) Carbon sequestration in a boreal forest ecosystem: results from the ecosystem simulation model, FORECAST. *Forest Ecology and Management,* **169,** 123-135.

Selig MF, Seiler JR, Tyree MC (2008) Soil Carbon and CO2 Efflux as Influenced by the Thinning of Loblolly Pine (Pinus taeda L.) Plantations on the Piedmont of Virginia. *Forest Science,* **54,** 58-66.

Shan J, Morris LA, Hendrick RL (2001) The Effects of Management on Soil and Plant Carbon Sequestration in Slash Pine Plantations. *Journal of Applied Ecology,* **38,** 932-941.

Skovsgaard JP, Stupak I, Vesterdal L (2006) Distribution of biomass and carbon in even-aged stands of Norway spruce (<i>Picea abies</i> (L.) Karst.):A case study on spacing and thinning effects in northern Denmark. *Scandinavian Journal of Forest Research,* **21,** 470 - 488.

Slesak RA, Schoenholtz SH, Harrington TB (2010) Soil Respiration and Carbon Responses to Logging Debris and Competing Vegetation. *Soil Sci. Soc. Am. J.,* **74,** 936-946.

Snyder MA, Bell JL, Sloan LC, Duffy PB, Govindasamy B (2002) Climate responses to a doubling of atmospheric carbon dioxide for a climatically vulnerable region - art. no. 1514. *Geophysical Research Letters,* **29,** 1514.

Solomon S, Qin D, Manning M, *et al.* (2007) Technical Summary. In *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* (eds Solomon S, Qin D, Manning M, *et al.*). Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Strong T (1997) Harvesting intensity influences the carbon distribution in a northern hardwood ecosystem. *Research Paper NC-329 U.S. Dept. of Agriculture, Forest Service, North Central Research Station.*

Swanston C, Homann PS, Caldwell BA, Myrold DD, Ganio L, Sollins P (2004) Long-term effects of elevated nitrogen on forest soil organic matter stability. *Biogeochemistry,* **70,** 229-252.

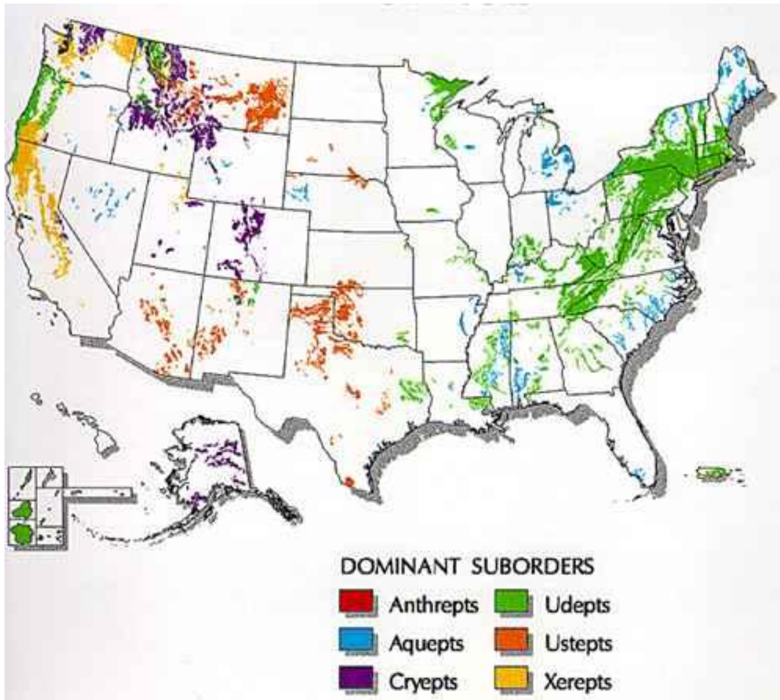
Tingey DT, Lee EH, Waschmann R, Johnson MG, Rygiewicz PT (2006) Does soil CO2 efflux acclimatize to elevated temperature and CO2 during long-term treatment of Douglas-fir seedlings? *New Phytologist,* **170,** 107-118.

Waldrop MP, Zak DR, Sinsabaugh RL, Gallo M, Lauber C (2004) NITROGEN DEPOSITION MODIFIES SOIL CARBON STORAGE THROUGH CHANGES IN MICROBIAL ENZYMATIC ACTIVITY. *Ecological Applications,* **14,** 1172-1177.

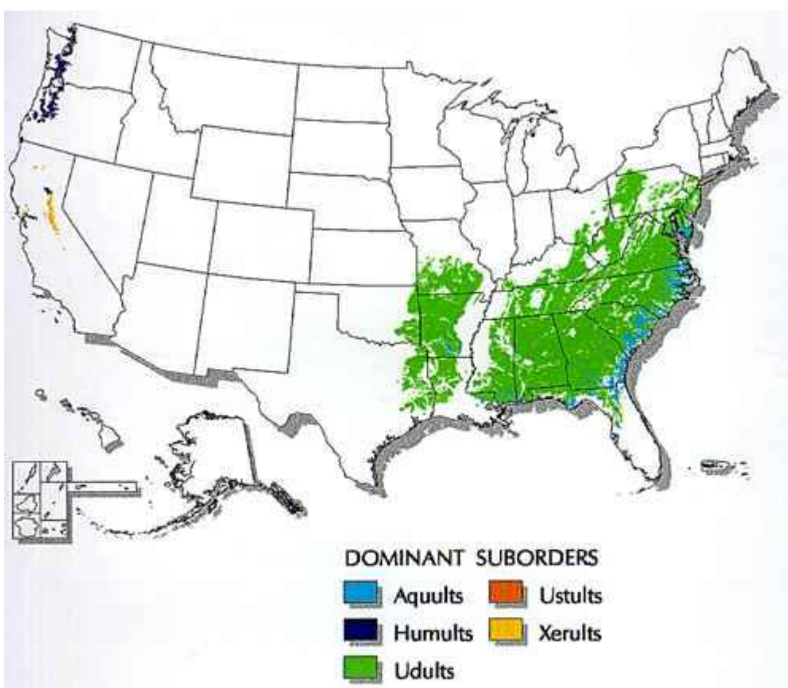
Woodbury PB, Smith JE, Heath LS (2007) Carbon sequestration in the U.S. forest sector from 1990 to 2010. *Forest Ecology and Management,* **241,** 14-27.

Yanai RD, Currie WS, Goodale CL (2003) Soil Carbon Dynamics after Forest Harvest: An Ecosystem Paradigm Reconsidered. *Ecosystems,* **6,** 197-212.

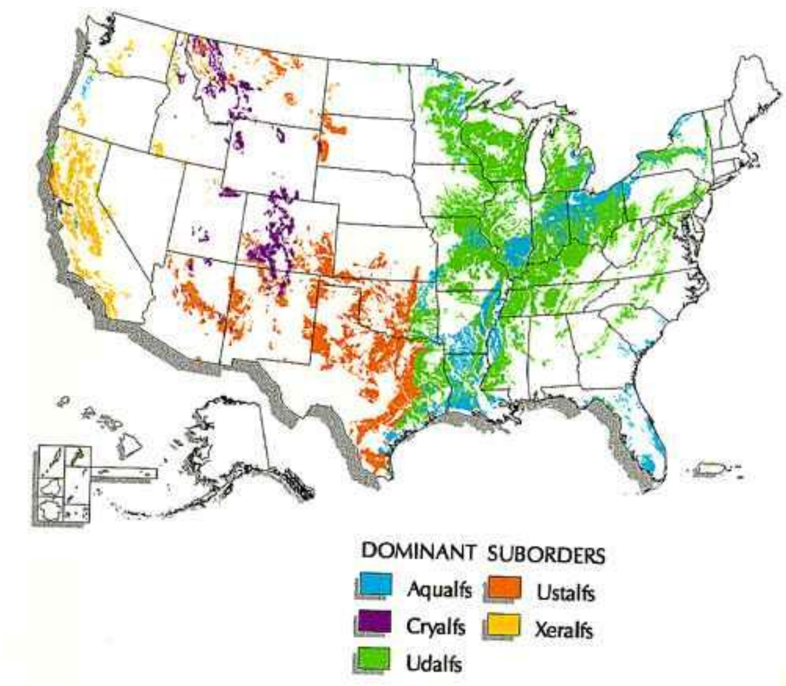
Appendix 1: Distribution of four main soil types in the United States



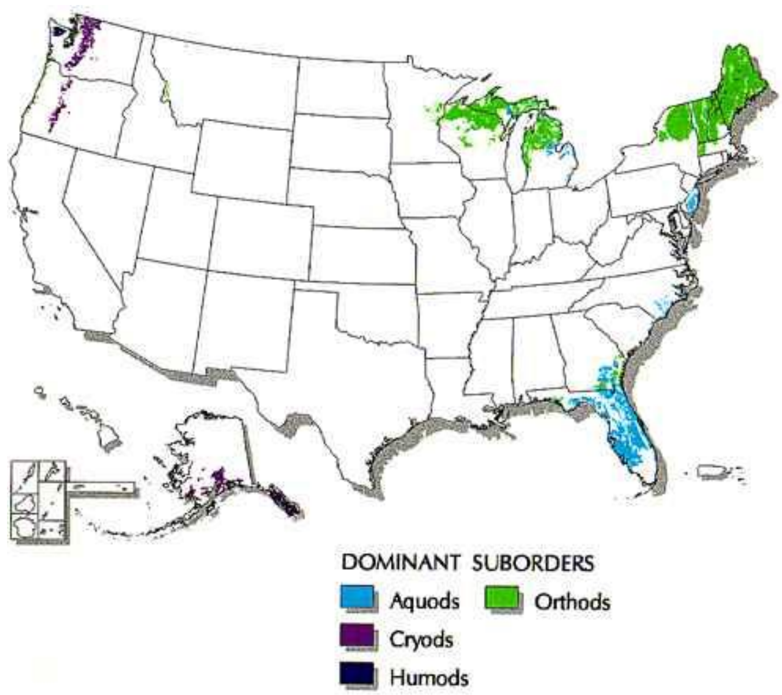
Inceptisols (Source: USDA NRCS)



Ultisols (Source: USDA NRCS)



Alfisols (Source: USDA NRCS)



Spodosols (Source: USDA NRCS)