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Report NRS-57

An Annotated Bibliography of Scientific Literature on Managing Forests for Carbon Benefits

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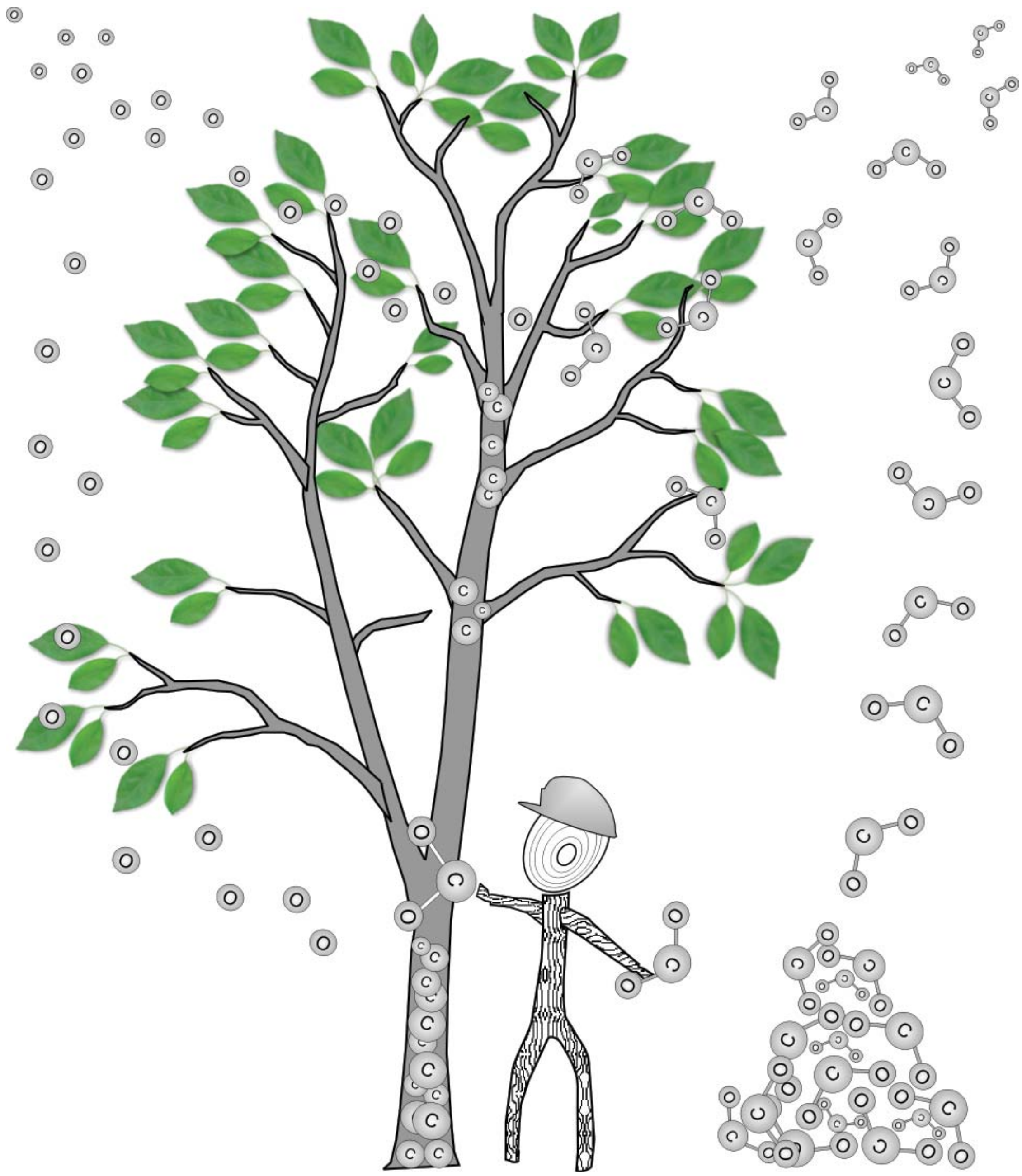

Abstract

Managing forests for carbon benefits is a consideration for climate change, bioenergy, sustainability, and ecosystem services. A rapidly growing body of scientific literature on forest carbon management includes experimental, modeling, and synthesis approaches, at the stand- to landscape- to continental-level. We conducted a search of the scientific literature on the topic of managing forests for carbon, and compiled an annotated list of citations. We chose to focus specifically on studies that addressed carbon in aboveground carbon pools, at both the micro (tree, stand) and macro (landscape, policy) levels. Aboveground pools include: live tree, understory, standing dead wood, down dead wood, and forest floor. The temporal scope of the literature search was the period 2000-2008 and the geographical scope was the temperate and boreal forests mainly in the United States, but also Canada, Europe, Russia, Japan, China, New Zealand, and Australia. The annotated bibliography is available at: http://www.nrs.fs.fed.us/pubs/ as a printable document; the references included in the bibliography are also available as a downloadable Endnote™ database or basic text file. The CD-ROM included with this publication contains the datasase and text files.

The Authors

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INTRODUCTION

Scientists and many policy-makers acknowledge that land-use change and forestry play a significant role in the global carbon cycle. Deforestation, which is a type of land-use change, and poor management practices such as degradation of global forests contributed 17.4 percent of global greenhouse gas releases in 2004 (IPCC 2007). When sustainably managed, forests can help mitigate climate change by sequestering atmospheric carbon dioxide in biomass and soils. In the United States, forests and products are estimated to sequester a net 745 Tg CO_2 under current land use and management practices (U.S. EPA 2008), offsetting as much as 20 percent of U.S. fossil fuel emissions (U.S. CCSP 2008a). Estimates suggest that the potential sequestration for U.S. forests may be in the range of 1500 to 2300 Tg CO_2 per year (Heath et al. 2003).

This bibliography represents a compilation of literature on the topic of the effects of forest management on carbon stocks or fluxes published in the years 2000-2008. It is intended as a starting point for scientists and managers regarding forest-based mitigation of climate change, as well as background information at the strategic level for mitigation opportunities. Pronounced climate change effects on our nation's forests and grasslands are beginning to be noticed (U.S. CCSP 2008b), so land managers are under increasing pressure and scrutiny to manage forests to be resilient to, and preventive of, climate change. What management practices, employed in which scenarios, can contribute to mitigation? This question is complex with informed answers often requiring a combination of global, regional, and local-scale data, and an intimate understanding of forest management practices and options considered with the uncertainty of climate change and other natural disturbances. Managers of public lands with multiple-use mandates are required to balance and prioritize multiple, sometimes competing objectives. In some regions or for some ownerships, mitigation practices may focus on maximizing landscape-level ecosystem carbon stocks while considering uncontrollable disturbances, while in other regions or for other landowners, objectives may focus on sustaining or increasing carbon sequestration in wood and bioenergy products which are a substitution for fossil fuel intensive products. In all scenarios, land managers may question whether, when, and how management practices such as thinning and fuel treatments create net benefits for the climate, or whether amendments should be used to enhance growth and productivity. In Figure 1, the red arrows depict emissions and sequestration by or within the forestry sector; the green arrows represent emissions outside of this sector. It should be noted that biofuels that substitute for fossil fuels prevent the release of fossil fuel-related emissions.

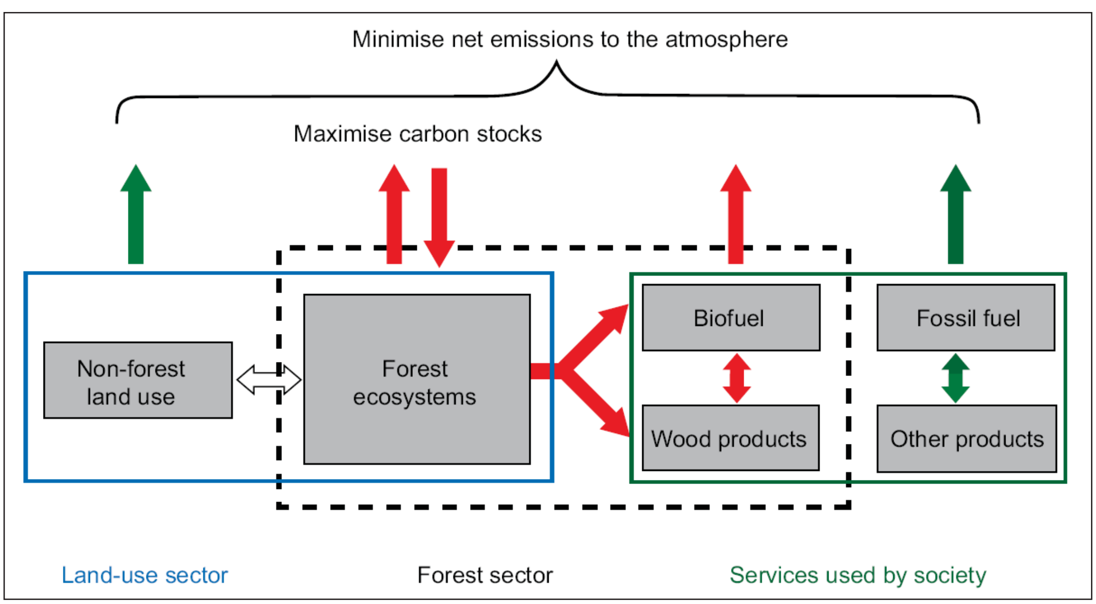

Figure 1.—Forest sector mitigation strategies need to be assessed with regard to their impacts on carbon storage in forest ecosystems, on sustainable harvest rates, and on net GHG emissions across all sectors. (Figure from Nabuurs et al. 2007, used with permission.)

THE BIBLIOGRAPHY

Purpose

This annotated bibliography is intended primarily as a reference for land managers who are seeking to understand the effects of forest management activities and climate-induced changes on the carbon stocks and fluxes of a stand or landscape. Each study listed in the bibliography is followed by a concise summary of its methods and primary results. The compilation should be helpful to managers of federal land and wildlife management agencies, and managers in the private sector, to show their land management decisions are taking into account 'best available science' (APA 1946, U.S. GAO 2003, NFMA 1976). At a strategic level, the Resources Planning Act (1974) requires the U.S. Secretary of Agriculture to conduct an assessment of the Nation's renewable resources every 10 years. Subsequent amendments require an analysis of the rural and urban forestry opportunities to mitigate the buildup of atmospheric carbon dioxide and reduce the risk of global climate change. This compilation helps identify forest management opportunities for the RPA Assessment.

Scope

This bibliography includes studies and papers which examine the effects of forest management activities on all aboveground forest carbon pools, at both the micro (tree, stand) and macro (landscape, policy) levels. Aboveground pools include: live tree, understory, standing dead wood, down dead wood, and forest floor. Aboveground pools are generally more dynamic than the soil carbon pool and are more dramatically affected by near-term management activities. Soil carbon is a critically important component of the terrestrial carbon pool and can be dramatically altered by land-use change, but soil carbon studies are often specialized and focus only on soil carbon, whereas our focus is on the entire forest. There are existing bibliographies of forest management and its effects on soil carbon (Heath and Smith 2000, Johnson and Curtis 2001, Hoover 2003), as well as an extensive discussion of the potential of U.S. forests to sequester carbon (Kimble et al. 2003), so our focus is on studies that include all forest pools or at least most aboveground carbon pools.

Because continued forest-based mitigation of climate change is dependent upon forests' successful adaptation to climate change, the literature and consequently this bibliography also includes limited related studies on forest management for adaptation. The geographic scope includes temperate and boreal forests in North America, Europe, Russia, Japan, China, New Zealand, and Australia. Forest management activities included in this bibliography consist of: afforestation/reforestation, amendment application, avoided deforestation, fuels treatment, harvesting, rotation length, general management intensity decisions, and species selection decisions. Incidental or involuntary climate effects include climate-driven natural disturbances (fire, insects or disease), involuntary fertilization (carbon dioxide and nitrogen deposition), changing weather patterns, and changing climate (temperature and precipitation) over the long term. Publications are also drawn from optimization studies; carbon flux analyses; studies of afforestation, reforestation, or avoided deforestation; economic analyses; and climate change feedback and effects.

At the time of publication, this bibliography contains 171 publications sorted into five broad categories: 1) experiments and observations, 2) models, 3) experiments with some pools modeled, 4) literature reviews and meta-analyses, and 5) policy perspectives. All publications listed include brief summaries of findings relevant to managing forests for carbon, especially aimed at forest-based mitigation of climate change. To the extent that they provide carbon pool data, carbon flux studies have been included (e.g., Pacala et al. 2001). And to the extent that they focus substantially on aboveground carbon pools, studies that include effects of management activities on soil carbon have also been included. However, studies focused exclusively on soil carbon are not included in the scope of this bibliography. In some cases, studies with an explicit focus on net ecosystem productivity (NEP) or net primary productivity (NPP) have been included because the results include or draw conclusions about effects on carbon stocks.

Using this Bibliography

This annotated bibliography is available as a downloadable and printable document; the references included in the bibliography are also available as a downloadable Endnote™ database or basic text file. For ease of use, the Appendix (beginning on page 44) provides summary tables containing all abbreviations of chemical elements and compounds, acronyms, tree scientific names used and corresponding common names, and units of measure and conversions used in this bibliography. This publication is available on our website at: http://www.nrs.fs.fed.us/pubs/. We are considering options for keeping this publication up-to-date into the future; check back at the NRS website for the most recent updates.

Categories

I. Experiments and observations
This category contains results of lab and field-based experiments and observation studies that explore the effects of a wide range of planned management activities and incidental or involuntary climate-related effects on carbon storage in natural and plantation forests.

II. Models
This wide-ranging category covers the diversity of models designed to forecast the potential effects of forest management decisions and/or changing climatic conditions and future scenarios and/or shifting and uncertain socioeconomic factors on carbon storage in forests, at the stand-level to the country-level. The category also includes studies that present carbon balance and flux data, forecasts, tradeoffs, or optimization results from models.

III. Experiments with some pools modeled
This category includes designed studies with field plots. These studies may report several years of experimental results and findings, but rely on models to forecast future carbon storage. Studies that compare experimental and modeled results are also included in this category.

IV. Literature reviews and meta-analyses
This category includes broad-scale reviews and seminal synthesis papers which, by definition, rely on a variety of other sources to: 1) compile “big-picture” estimates of current or potential or both current and potential carbon storage by forests, 2) describe ways in which forest management, or land-use change, or both has or can affect carbon pools and cycling, or 3) describe likely effects of climate change and involuntary fertilization on forest health, productivity, and carbon cycling and storage.

V. Policy Perspectives
This category contains those studies that draw attention to considerations of importance to the creation, design, and implementation of policy to effectively mitigate climate change. The papers may be either explicit (contain specific policy recommendations) or may be more scientific in nature (highlighting uncertainties and considerations without suggesting policy measures), but because of their general or high-level nature are critical to informing forest carbon policy-related dialogue. In some cases, papers in this category may explicitly explore forest management decisions as described in “Experiments and observations” (category 1), but from a high-level regional or national perspective. Thus, study conclusions are useful for broad-scale policy uses, rather than stand or forest-level management decisions.

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I. Experiments and Observations: Management and Climate Effects

1. Adams, A.B.; Harrison, R.B.; Sletten, R.S.; Strahm, B.D.; Turnblom, E.C.; Jensen, C.M. 2005. **Nitrogen-fertilization impacts on carbon sequestration and flux in managed coastal Douglas-fir stands of the Pacific Northwest.** Forest Ecology and Management. 220:313-325.

This study examines the effects of urea applications from1972 to 1996 on C sequestration in tree biomass and soils in *Pseudotsuga menziesii* for two soil types in western Washington. SOC was measured at four depths to a total of 1 m. Three to four applications of urea generally increased C density of both tree biomass and soils (average of 161 Mg C/ha vs. 135 Mg C/ha for tree biomass on fertilized vs. unfertilized sites, respectively; average of 260 Mg C/ha vs. 175 Mg C/ha for soil, respectively). Authors note that scope of study is limited due to small sample size and variation of field installations. Because of this, they paired their data with Canary et al. (2001), analyzed for total C, and found an average increase of 82.8 Mg C/ha for both biomass and soils at seven sites. Authors extrapolate over 10 million acres of intensively managed *Pseudotsuga menziesii* in the region, which yields an additional theoretical sequestration of 828 Tg C, but the study cautions that because all stands in the area are not of the same age and type, their assessment should not be widely applied.

2. Barford, C.C.; Wofsy, S.C.; Goulden, M.L.; Munger, J.W.; Pyle, E.H.; Urbanski, S.P.; Hutyra, L.; Saleska, S.R.; Fitzjarrald, D.; Moore, K. 2001. **Factors controlling long- and short-term sequestration of atmospheric CO_2 in a mid-latitude forest.** Science. 294: 1688-1691.

This paper reports on 9 years of CO_2 flux measurements for a 60- to 80-year-old northern hardwood forest (Harvard Forest) and compares results to biometric measurements of changes in live and dead wood pools for selected species. Findings from the flux study show net CO_2 uptake of 2.0 +/- 0.4 Mg CO_2/ha/yr (0.55 +/- 0.11 Mg C/ha/yr) from 1993-2000, while the biometric measurements show a similar uptake of 1.6 +/- 0.4 Mg CO_2/ha/yr (0.44 Mg C/ha/yr +/- 0.11 Mg C/ha/yr).

The study reports that interannual carbon sequestration is affected in large part by previous management and the impacts of prior disturbances, whereas year-to-year fluctuation in uptake is more a function of weather.

3. Balboa-Murias, M.Á.; Rodríguez-Soalleiro, R.; Merino, A.; Álvarez-González, J.G. 2006. **Temporal variations and distribution of carbon stocks in aboveground biomass of radiata pine and maritime pine pure stands under different silvicultural alternatives.** Forest Ecology and Management. 237: 29-38.

This study examines the impact of five site qualities, three stocking densities, and five thinning intensities on aboveground biomass C sequestration in *Pinus pinaster* and *Pinus radiata* in plantation forests of northwest Spain, a region characterized by mild temperatures and a slight hydric deficiency in summer. *P. radiata* has a higher NPP than *P. pinaster*, so total aboveground biomass C storage was greater for the former species. For *P. radiata*, mean annual C storage could be increased by 3.0 Mg/ha by choosing the highest stocking density, the best site quality, and the least intense thinning regime (15 percent). For the same scenario with maritime pine, annual C sequestration could be increased by 2.4 Mg/ha. Increasing the rotation age from 30-40 years yielded an increase in biomass of 33-38 percent, but mean annual C storage declined. This study concludes that sustainable management that seeks to optimize biomass production and C sequestration benefits most from good site quality, reduced thinning intensity, and extended rotation lengths.

4. Boerner, R.E.J.; Huang, J.; Hart, S.C. 2008. **Fire, thinning, and the carbon economy: effects of fire and fire surrogate treatments on estimated carbon storage and sequestration rate.** Forest Ecology and Management. 255: 3081-3097.

This study examines effects of prescribed fire, mechanical treatments designed as surrogates for prescribed fire, and combination treatments (mechanical plus fire) on ecosystem C stocks at 12 study sites in the eastern and western United States. They found that while prescribed fire had little impact on forest C budgets in eastern forests, mechanical or combination treatments converted the forests from net sinks to sources in the first years following treatment, primarily due to a loss of aboveground biomass. Carbon budgets in western forests remained relatively stable, regardless of treatment. Overall, total ecosystem C across the network of sites was not significantly affected by prescribed fire, though several individual sites did experience significant losses ($p<.05$); average net losses from mechanical or mechanical plus fire ranged from 4-20 Mg/ha after 3 years (initial losses were often mitigated by increased uptake post-treatment), but only the losses in year 1 were significant ($p<.05$). Findings suggest that optimal forest management for fire, harvesting, and sequestration varies significantly between eastern and western forests. Authors do not directly address to what extent treatments reduce risk of catastrophic wildfire, and how this would affect C budgets, but do reference a variety of studies that indicate reduced U.S. forest sink-strength due to historical and continued fire suppression.

5. Bond-Lamberty B.; Wang C.K.; Gower S.T. 2004. **Net primary production and net ecosystem production of a boreal black spruce wildfire chronosequence.** Global Change Biology. 10: 473-487.

Examines the C dynamics of a chronosequence of seven stands of *Picea mariana* of different ages in the Canadian BOREAS Northern Study Area, west of Thompson, Manitoba. The seven stands resulted from stand-replacing wildfires around 1850 and in 1930, 1964, 1981, 1989, 1995, and 1998. The NPP of stands in well and poorly drained sites were lowest in the years immediately following fire (0.5-1.0 Mg C/ha) and highest 12-20 years following fire (3.32 in dry stands and 5.21 Mg C/ha in wet stands. NPP in the older stands was about half that in the 12-20 year old stands. For the entire chronosequence, NPP on dry sites ranged from 1.06-4.06 Mg C/ha, and NPP on wet sites ranged from 0.72-5.34 Mg C/ha. The study includes a summary table that includes NPP on dry and wet stands for each age according to aboveground and belowground measurements.

6. Bradford, J.B.; Birdsey, R.A.; Joyce, L.A.; Ryan, M.G. 2008. **Tree age, disturbance history, and carbon stocks and fluxes in subalpine Rocky Mountain forests.** Global Change Biology. 14: 2882-2897.

This study examines the relationship among tree age, history of stand disturbance, and forest C storage and cycling on seven stands at three sites to determine whether either age, disturbance history, or both can be used to predict C stocks and fluxes for three distinct subalpine central Rocky Mountain forest ecosystems (Fraser Experimental Forest, Glacier Lakes Ecosystem Experimental Site (GLEES), Niwot Ridge Ameriflux Study Site). The sites differed in tree age, disturbance history, species composition, elevation, and precipitation, but ecosystem C storage was similar (roughly 260 Mg C/ha at Fraser and Niwot and 330 Mg C/ha at GLEES), with 80-90 percent of live C stored in trees. "Maximum tree age overestimated time since disturbance for young forests and underestimated it for old forests," making tree age a poor predictor of disturbance history. Tree age and disturbance history influenced both C pools and fluxes, but there is little change after the first 100 years has passed following a disturbance. Because of this, the study concludes that landscape-scale estimates can be simplified by treating subalpine forests in this region as a single forest type and that the 100 years following a disturbance is the most critical factor affecting C change.

7. Canary, J.D.; Harrison, R.B.; Compton, J.E.; Chappell, H.N. 2000. **Additional carbon sequestration following repeated urea fertilization of second-growth Douglas-fir stands in western Washington.** Forest Ecology and Management. 138: 225-232.

Effects of urea application over a 16-year period are examined for *Pseudotsuga menziesii* stands (age 62-69 at study's end) in western Washington. Average aboveground tree C increased by 26.7 Mg C/ha over the control during the 16-year period (significant at $p<.01$), or 1.7 Mg C/ha on an annualized basis (though increases likely were not constant). Total ecosystem C increased by 34.8 Mg C/ha over the control (2.2 Mg/ha on an annualized basis, though increases were likely not constant), but differences in individual snag, soil, and understory pools were not significant. The findings emphasize the importance of tracking soil C below the surface horizons; 75 percent of soil C (to a depth of 85 cm) was found below the A-horizon.

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The study examines the relative importance of land-use history and CO_2 fertilization, N deposition, and climate change on the C uptake of forests in Minnesota, Michigan, Virginia, North Carolina, and Florida. Comparison FIA data (includes estimates of aboveground biomass, growth- and mortality-related changes in aboveground biomass, and stand age) from the late 1970s/early 80s to the mid 1990s were used for 20,000 plots; results indicate that growth enhancement (defined as CO_2 fertilization and N deposition) accounted for only 2.0 +/- 4.4 percent of aboveground NEP.

9. Chiang, J.-M.; McEwan, R.W.; Yaussy, D.A.; Brown, K.J. 2008. **The effects of prescribed fire and silvicultural thinning on the aboveground carbon stocks and net primary production of overstory trees in an oak-hickory ecosystem in southern Ohio**. Forest Ecology and Management. 255: 1584-1594.

This study examines the impacts of thinning and prescribed burns on *Quercus* recruitment and regeneration, and assesses changes in C storage and ANPP due to thinning/burning treatments. Estimated pretreatment aboveground biomass was 233 Mg/ha, and thinning resulted in a 30 percent reduction in aboveground biomass. Authors did not trace the carbon lost from thinning practices to determine how much was ultimately retained in long-term wood products, but did find a substantial but transient reduction in ANPP in thinned stands for both field measurements and ancillary model simulations that directly replicated the field experiment. Prescribed burning has a significant impact ($p<.05$) on the mortality of stems (of both *Acer* and *Quercus*; the latter was less fire-resistant than is typically expected) but did not significantly affect ANPP. Neither thinning nor burning has a long-term impact on C uptake in these forests.

10. Coyle, D.R.; Coleman, M.D. 2005. **Forest production responses to irrigation and fertilization are not explained by shifts in allocation.** Forest Ecology and Management. 208: 137-152.

This study examines aboveground and belowground growth and biomass accumulation response of two *Populus deltoides* clones and *Platanus occidentalis* that received irrigation (I), fertilization (F), or a combination treatment (IF) in South Carolina. Total biomass (branch, bark, wood, stump, coarse and fine root) response of nearly every tree to both I and F treatments (40, 80, 120 kg N/ha/yr for years 1, 2, 3, respectively) was significant ($p< .05$). Trees that received the IF treatment accumulated significantly more biomass than those in other treatments ($p<.05$). *P. occidentalis* that received the IF treatment had the most significant gain in biomass C gain, with a mean annual increase of 6.8 Mg C/ha/yr; combination treatments for the *P. deltoides* clones yielded increases of 3.9 and 3.5 Mg C/ha/yr. These was no significant difference between root and shoot allocation.

11. Curtis, P.S.; Hanson, P.J.; Bolstad, P.; Barford, C.; Randolf, J.C.; Schmid, H.P.; Wilson, K.B. 2002. **Biometric and eddy-covariance based estimates of annual carbon storage in five North American deciduous forests.** Agricultural and Forest Meteorology. 113: 3-19.

This study examines and compares annual C storage for five deciduous U.S. forest sites of similar age, canopy height, and stand basal area across Tennessee, Indiana, Massachusetts, Michigan, and Wisconsin. Meteorological and biometric measurements of C storage were compared over time. Biometric measurements indicated an NEP of between 0.7-3.5 Mg C/ha/yr among the sites (highest in south-central Indiana, lowest in upper Michigan), with an average of 1.9 Mg C/ha/yr, while the meteorological model results yielded values of about 3.0-5.0 Mg C/ha/yr for aboveground net primary productivity (the higher values corresponded to more southern sites). The study states that differences in biometric NPP estimates correlated to expectations based on site-specific soil and climate differences. There were no major differences between biometric and meteorological estimates for same-site comparisons, and differences were smaller when "fewer belowground processes were explicitly incorporated into the estimates."

12. Finkral, A.J.; Evans, A.M. 2008. **The effects of a thinning treatment on carbon stocks in a northern Arizona ponderosa pine forest.** Forest Ecology and Management. 255: 2743-2750.

The study examines the C consequences of restoration thinning practices designed to reduce wildfire risk on the aboveground C balance of a *Pinus ponderosa* forest in Arizona. Treatment reduces risk of catastrophic fire, but it still results in a one-time net loss of 3.11 Mg C/ha. Simply using the slash to create long-lived wood products (rather than burning) results in C benefits of 3.35 Mg C/ha. This finding that has important implications for hazardous fuels treatments throughout the western United States.

13. Fitzsimmons, M.J.; Pennock, D.J.; Thorpe, J. 2004. **Effects of deforestation on ecosystem carbon densities in central Saskatchewan, Canada.** Forest Ecology and Management. 188: 349-361.

Findings from Saskatchewan, Canada indicate that forests store nearly twice as much C as compared to cultivated fields (158 vs. 81 Mg C/ha, respectively). Conversion of forest to agricultural land would result in near-term C losses of at least 30 Mg C/ha. Reforestation of pasture and agricultural land with trembling aspen could sequester 30-75 Mg C/ha over a 50- to 100-year time horizon.

14. Foster, N.W.; Morrison, I.K. 2002. **Carbon sequestration by a jack pine stand following urea application**. Forest Ecology and Management. 169: 45-52.

The study examines C accumulation response of semi-mature *Pinus banksiana* stands in Ontario, Canada to the application of a one-time N amendment of 0 (control), 56, 112, 224, or 448 kg N/ha. There is no significant difference in the long-term (30-year) net C accumulation of the stands. However, there is a statistically significant increase ($p<.05$) in diameter at breast height (d.b.h.) increment over the codominant species at year 10, suggesting that urea application 10 years before harvest can increase timber yield. The study concludes that over-stocked, semi-mature *P. banksiana* stands should be given low priority when considering nutrient amendments, but states that C accumulation may have been constrained by other nutrients and a combination N/P/K amendment may lead to substantial long-term aboveground accumulation of C.

15. Giasson, M.-A.; Coursolle, C.; Margolis, HA. 2006. **Ecosystem-level CO_2 fluxes from a boreal cutover in eastern Canada before and after scarification.** Agricultural and Forest Meteorology. 140: 23-40.

This study uses CO_2 flux towers and the eddy covariance technique to study the effects of scarification on NEP of a recently harvested boreal *Picea mariana*/*Pinus banksiana* stand in Quebec, Canada. Scarification was necessary to produce adequate regeneration, yet the treatment, which destroyed 60 percent of the aboveground biomass, resulted in the site becoming a notably greater C source following treatment (1.11 Mg C/ha before vs. 1.75 Mg C/ha after treatment). Scarification resulted in biomass destruction and daily NEP was lower for the year following treatment. The findings suggest that cutovers may account for emissions of 5 Mt C/yr in Canada (generalized to all Canadian boreal ecosystems. This study does not make mention of whether or to what extent scarification eventually (year 5 and beyond) leads to greater C uptake in regenerated stands.

16. Gough, C.M.; Vogel, C.S.; Harrold, K.H.; George, K.; Curtis, P.S. 2007. **The legacy of harvest and fire on ecosystem carbon storage in a north temperate forest.** Global Change Biology. 13: 1935-1949.

This study examines the effects of disturbances (clearcut and subsequent burn) on C storage in a mixed deciduous forest in the northern Lower Peninsula of Michigan. Although stands that were repeatedly disturbed reverted to sinks within 6 years of disturbance, the long-term trajectory and overall capacity of C storage was limited. Repeated disturbances (a second harvest and fire) reduced site quality and resulted in annual C storage that was 45 percent lower than that in the reference stand receiving a single harvest-fire disturbance. Maximum annual C storage that was 26 percent lower than that in the reference stand over a 62-year period. Previous harvesting regimens that reduced site quality continue to limit C sequestration in these areas.

17. Gough, C.M.; Vogel, C.S.; Schmid, H.P.; Curtis, P.S. 2008. **Controls on annual forest carbon storage: lessons from the past and predictions for the future.** BioScience. 58: 609-622.

In this study, authors use a combination of ecological and meteorological approaches to measure annual forest C storage from 1999-2005 in a mixed deciduous forest in Michigan's northern Lower Penninsula. The area is representative of 102,000 km^2 of forest in the upper Midwest that is dominated by *Populus grandidentata* and *Populus tremuloides*. The study examines the response of annual C storage to historical disturbances, and finds that repeated clearcut harvests followed by fire result in lower overall ecosystem C storage capacity. In this ecosystem (average stand age 85 years, with stands ranging in age from 6-90 years), net C gain was about 1.5 Mg C/ha/yr, a rate typical of other aspen-dominated forests. The study concludes: "Effective forest C sequestration requires management of all C pools, including traditionally managed pools such as bole wood and also harvest residues and soils."

18. Guo, L.B.; Bek, E.; Gifford, R.M. 2006. **Woody debris in a 16-year-old *Pinus radiata* plantation in Australia: Mass, carbon and nitrogen stocks, and turnover.** Forest Ecology and Management. 228: 145-151.

Authors examine the C density of woody debris on afforested (with *Pinus radiata*) former pastureland in Australia. A previous meta-analysis spanning temperate, tropical, and subtropical forests in 16 countries demonstrated that soil C stocks decreased following conversion of native pasture to forest plantation (Guo and Gifford 2002). This study hypothesizes that soil C loss from land-use change is at least partially offset by gains in the woody debris pool. Woody debris contained 3.1 Mg C/ha in a 16-year-old *Pinus radiata* plantation 8 years after thinning and pruning activities, which represents approximately 22 percent of soil carbon reduction from previous land-use change. The pine plantation was a net C sink because gains in aboveground biomass exceeded SOC losses. The decay of woody debris is influenced by resource quality and environmental conditions such as temperature, moisture, aeration, and decomposer organisms. The publication contains extensive data on decomposition and C release rate for various species and diameter classes of pine.

19. Harmon, M.E.; Bible, K.; Ryan, M.G.; Shaw, D.C.; Chen, H.; Klopatek, J.; Li, X. 2004. **Production, respiration, and overall carbon balance in an old-growth *Pseudotsuga-Tsuga* forest ecosystem.** Ecosystems. 7: 498-512.

This study uses ground-based measurements to determine the GPP, NPP, NEP, and autotrophic and heterotrophic respiration of an old-growth *Pseudotsuga-Tsuga* forest at the Wind River Experimental Forest in Washington. The study reports average values for live C stores (39.8 Mg C/ha), detritus and mineral soil (22.1 Mg C/ha) and total C (61.9 Mg C/ha), and finds a weak sink of approximately 0.2 Mg C/ha/yr. These results differ from estimates using an eddy-flux method but the difference could be the result of a temporal mismatch between datasets.

20. Hicke, J.A.; Asner, G.P.; Kasischke, E.S.; French, N.H.F.; Randerson, J.T.; Collatz, G.J.; Stocks, B.J.; Tucker, C.J.; Los, S.O.; Field, C.B. 2003.

Postfire response of North American boreal forest net primary productivity analyzed with satellite observations. Global Change Biology. 9: 1145-1157.

This study uses a 17-year record of satellite NDVI observations to identify fire scars across the North American boreal landscape and determine NPP in post-burn years in these fire-scarred areas using the CASA carbon-cycle model. NPP decreased by an average of 0.6-2.6 Mg C/ha (30-80 percent). On average, recovery period for boreal forests is about 9 years, though results vary substantially among fires.

21. Howard, E.A.; Gower, S.T.; Foley, J.A.; Kucharik, C.J. 2004. **Effects of logging on carbon dynamics of a jack pine forest in Saskatchewan. Canada.** Global Change Biology. 10: 1267-1284.

This study measures the NPP of a chronosequence of five *Pinus banksiana* stands in Saskatchewan, Canada that was part of the southern area of the BOREAS study site. The four younger stands (0, 5, 10, and 29 years old) had been harvested; the oldest (79 years old) originated following wildfire. Average NPP measurements on each stand were positive: 0.9, 1.3, 2.7, 3.5, and 1.7 Mg C/ha, respectively, but NEP, which takes into account heterotrotrophic respiration by soils, was negative for the two youngest and the oldest stand, and only slightly positive (0.4) for the 10- and 29-year-old stands. Spatial and methodological uncertainties limit conclusions, but results show that stands become an atmospheric C source in the years following logging.

22. Hubbard, R.M.; Vose, J.M.; Clinton, B.D.; Elliott, K.J.; Knoepp, J.D. 2004. **Stand restoration burning in oak-pine forests in the southern Appalachians: effects on aboveground biomass and carbon and nitrogen cycling.** Forest Ecology and Management. 190: 311-321.

The study considers the effects of understory prescribed burning on forest biomass and C pools on oak-dominated forest stands with fine-loamy, mixed, mesic soils in southern Tennessee and Georgia. There was no significant difference ($p>0.1$) in total aboveground live woody biomass between burned and control plots. However, in burned plots, understory biomass alone was reduced by 50 percent ($p=.07$) and overstory biomass was reduced by 11 percent, but the difference in the latter case was not significant. Burning significantly reduced ($p<.01$) C pools in CWD, small wood, and litter. The total forest floor (CWD, small wood, litter, and humus) C pool was reduced by 4.05 Mg C/ha, but this difference was also not significant ($p> 0.1$). C flux was reduced on burned sites for 2 months following treatment, but then returned to normal. Monthly litterfall was not affected, suggesting that pools would be restored quickly. Prescribed burning can be an effective management tool that does not adversely affect C cycling or nutrient cycling.

23. Hazlett, P.W.; Gordon, A.M.; Sibley, P.K.; Buttle, J.M. 2005. **Stand carbon stocks and soil carbon and nitrogen storage for riparian and upland forests of boreal lakes in northeastern Ontario.** Forest Ecology and Management. 219: 56-68.

Research in northeastern Ontario, Canada to determine how forest management and harvesting activities may impact ecosystem C levels examined C and N storage in upland and riparian boreal forest ecosystems. Total, aboveground, and belowground C stocks did not differ significantly ($p>.05$) between upland and riparian stands (total C was 83.847 Mg C/ha riparian vs. 81.487 Mg C/ha upslope). However, in the riparian zones, a greater proportion of total C was stored in overstory stocks and floor layers were deeper and contained more C than upland sites. Because of these differences in C allocation between zones, similar harvesting techniques (whole-tree harvesting) removes far more aboveground and total C in riparian than upland boreal ecosystems (98 percent vs. 76 percent, respectively for aboveground; 35 percent vs. 17 percent respectively, for total ecosystem C). Because riparian ecosystems and the aquatic habitats they support are particularly sensitive to changes in nutrient levels, changes in harvesting techniques (selective, partial, modified) would result in greater C retention in these ecosystems, and likely faster postharvest regeneration due to greater nutrient availability.

24. Laclau, P. 2003. **Biomass and carbon sequestration of ponderosa pine plantationsand**

native cypress forests in northwest Patagonia. Forest Ecology and Management. 180: 317-333.

Conversion of pasture to pine plantations in northwest Patagonia resulted in little change in soil C but created an additional biomass sink of 3.5 Mg C/ha during the plantations' first 15 years. In significantly older but uneven-aged cypress stands that had been subject to intense grazing during previous harvests there was no significant difference in total ecosystem C from pine plantations, but significantly greater soil C (an additional 20 Mg C/ha more in cypress stands, to a depth of 50 cm). ANOVA revealed significant differences in soil C between forest types but not between land uses (forest vs. pasture). Converting cypress forests to pine plantations could result in substantial losses in soil C. Because cypress and pine grow on distinctly different soil types in the United States, and conversion from one forest type to the other may not be feasible, and conversion of pasture to forest should exceed the baseline pasture sequestration rate of 2.6 Mg C/ha.

25. Laiho, R.; Sanchez, F.; Tiarks, A.; Dougherty, P.M.; Trettin, C.C. 2003. **Impacts of intensive forestry on early rotation trends in site carbon pools in the southeastern U.S.** Forest Ecology and Management. 174: 177-189.

Intensive management of southern forest plantations has led to threefold increases in productivity, but management and harvesting effects on C pools is not completely understood. This study examines the effects of four harvesting strategies (stem only, whole tree, whole tree with forest floor removal, and full amelioration, consisting of whole tree, disking, bedding, and fertilization), in some cases combined with herbicide treatments, on C pools in managed forest plantations in North Carolina and Louisiana. The plantations consisted of 55-year-old mixed pine-hardwood stands, with *Pinus taeda* as the dominant species. Measurements were taken prior to harvest and 5 years following harvest. There were no substantial changes in the upper soil C profile (<30 cm) in the short term by treatment, but there were only three soil samples per plot on the North Carolina site. Site preparation may have positively influenced soil C pools. On the North Carolina site, the amount of organic matter removed played a larger role than herbicide treatment in influencing soil C; the opposite was true for the Louisiana site. Aboveground and soil C pools depended on both harvesting and site preparation methods and levels of significance varied among sites. Whole-tree harvesting reduced soil C ($p<.03$), amelioration and fertilization increased soil C in North Carolina ($p<.06$), herbicides reduced soil C in all cases in Louisiana, all treatments reduced forest floor C in North Carolina ($p<.06$), and whole-tree harvesting with or without herbicides reduced forest-floor C in Louisiana ($p<.06$).

26. Lee, J.; Morrison, I.K.; Leblanc, J.-D.; Dumas, M.T.; Cameron, D.A. 2002. **Carbon sequestration in trees and regrowth vegetation as affected by clearcut and partial cut harvesting in a second-growth boreal mixed wood.** Forest Ecology and Management. 169: 83-101.

The study examines the impacts of forest management practices (three silvicultural options: clearcut vs. shelterwood vs. uncut control; and two harvesting systems: tree-length vs. whole-tree removal) and post-harvest ecosystem C pools and recovery in boreal mixed-wood forests in Ontario, Canada. Dominant species were *Picea glauca, Picea mariana, Abies balsamea, Populus tremuloides,* and *Betula alba*. Post-harvest C assimilation rates for the clearcut and partial cut plots were similar and significantly greater ($p<.001$) than those for the control (uncut) plot. Also, total ecosystem sequestration was significantly greater ($p<.001$) on control than on partial vs. clearcut plots (roughly 3.1 Mg C/ha/yr vs. 1.8 Mg C/ha/yr vs. 0.3 Mg C/ha/yr) 5 years after harvest. Results demonstrate the rapid regrowth of ground vegetation followed by aspen thickets, which speeded the reconstitution of ecosystem C pools. C sequestration on partial-cut plots would have been closer to that of control plots had windthrow not occurred and more care been taken to minimize damage during harvesting operations. Although partial harvesting results in greater ecosystem C assimilation than clearcutting, this must be weighed against "lower productivity and higher costs" that result from partial cutting. This study did not account for carbon in harvested wood products.

27. Li, Q.; Chen, J.; Moorhead, D.L.; DeForest, J.L.; Jensen, R.; Henderson, R. 2007. **Effects of timber harvest on carbon pools in Ozark forests.** Canadian Journal of Forest Research. 37: 2337-2348.

This study compares the effects of no-harvest management, single-tree uneven-age management, and clearcut even-age management on forest C pools 8 years after treatment in the Missouri Ozarks. Dominant species were *Quercus alba*, *Quercus velutina*, *Quercus coccinea, Carya glabra,* and *Carya cordiformis*. Although ecosystem C (live tree, roots, CWD, forest-floor litter, and soil to a depth of 15 cm) was greatest for the no-harvest treatment (182 Mg C/ha), the single-tree uneven-age treatment contained 172 Mg C/ha and resulted in a 31 percent loss of C in the live-tree pool, compared with 130 Mg C/ha and a 93 percent decline in the live-tree C pool in the clearcut even-aged management treatment. However, differences in ecosystem C were significant ($p<.05$) for each treatment. Efforts to increase ecosystem C sequestration must consider C pool allocation patterns of specific ecosystems, and how management might reconfigure these pools. This study did not account for carbon in harvested wood products.

28. Litton, C.M.; Ryan, M.G.; Knight, D.H. 2004. **Effects of tree density and stand age on carbon allocation patterns in postfire lodgepole pine.** Ecological Applications. 14: 460-475.

The study examines how post fire C pools, fluxes, and allocation patterns varied among 13- and 110-year-old stands of *Pinus contorta* in Yellowstone National Park. The stands differed in tree density; C in biomass and detritus was estimated from direct sampling and allometric equations. Most of the C (91-99 percent) in young stands was detritus; in mature stands, 64 percent of the C was in live vegetation. In young stands, C (foliage, stems, coarse and fine roots) increased significantly ($p<.01$) with tree density and C in live vegetation increased significantly ($p<.01$) as stands matured. Total ecosystem C in each stand (13-year-old low, moderate, and high density stands, and 110-year-old mature stand) was 76.36, 70.00, 63.70, and 170.79 Mg C/ha, respectively. There was a constant ratio of ANPP and TBCA over time, implying that C allocation patterns in *P. contorta* are independent of stand age or tree density.

29. McCarthy, H.R.; Oren, R.; Kim, H.S.; Johnsen, K.H.; Maier, C.; Pritchard, S.G.; Davis, M.A. 2006. **Interaction of ice storms and management practices on current carbon sequestration in forests with potential mitigation under future CO_2 atmosphere.** Journal of Geophysical Research. 111: D15103.

Few estimates of future sequestration and C budgets account for the effects of nonfire disturbance on C sequestration and release. This study emphasizes the importance of considering the effects of ice storms, which "affect forest ecosystems on a range of timescales" (immediate tree mortality, reduced future productivity for damaged trees, reduced reproductive capacity for some species that produce seeds in the upper crown) and occur approximately once every 6 years in the southeastern United States. Practices designed to increase wood quality and/or yield, such as thinning and/or fertilization, can initially leave forests more vulnerable to damage from ice storms. (A recently thinned stand has low stand density and no crown-to-crown support, and it has been shown that fertilization reduced wood density and strength.) The effects of ice-storm damage were examined on thinned, fertilized, and control plots in both current and elevated CO_2 conditions (the latter through a FACE site). Fertilization resulted in no significant difference ($p>.10$), but thinned plots under current climate conditions suffered significantly greater damage than unthinned plots. Both types of plots incurred about 60 percent less damage under elevated CO_2 conditions. The study concludes that loblolly pine plantations, currently restricted by temperature and ice-storm constraints, could be expanded northward because they would experience less damage and mortality under elevated CO_2 conditions.

30. Morehouse, K.; Johns, T.; Kaye, J.; Kaye, M. 2008. **Carbon and nitrogen cycling immediately following bark beetle outbreaks in southwestern ponderosa pine forests.** Forest Ecology and Management. 255: 2698-2708.

This study examines the effects of bark beetle infestation on C and N pools and fluxes in stands of *Pinus ponderosa* in Arizona. Bark beetles have been a perennial source of low-level disturbance in pine forests, but this paper states that their impact has been magnified by drought and fire exclusion (it does not cite climate change as an exacerbating factor.) On sites with similar ecosystem structure before infestation, there were significant differences ($p<.05$) between infested and uninfested sites in live- and dead-tree C pools. Infested sites held 65 Mg C/ha (60 percent of aboveground biomass) in dead trees compared to 12 Mg C/ha (5 percent) in uninfested plots. There were significant differences in needle N-concentration (which was higher in infested plots due to premature needlefall) 3 years after infestation, but no differences in soil respiration rates between sites. This study notes that additional research is needed to better understand long-term C flux and storage impacts that result from significant tree mortality.

31. Mund, M.; Kummetz, E.; Hein, M.; Bauer, G.A.; Schulze, E.-D. 2002. **Growth and carbon stocks of a spruce forest chronosequence in central Europe.** Forest Ecology and Management. 171: 275-296.

The study attempts to isolate indirect and direct human impacts on forest growth in six monotypic *Picea abies* stands in Bavaria, Germany. Each stand was a different age (16, 35, 43, 72, 112, and 142 years old) but ecosystem conditions (acidic soils, high N deposition) were similar. Actual growth (independent of age) at both the tree and stand level exceeded that predicted by growth and yield tables, but growth was stimulated due to thinning and forest management. Carbon sink capacity in the future cannot be predicted by historical growth and yield tables based on undisturbed site conditions. The causes of altered growth remain unclear but might be related to increased CO_2 concentrations, N deposition, elevated temperature, and the effects of thinning and management (or combined synergistic effects).

32. Nilsen, P.; Strand, L.T. 2008. **Thinning intensity effects on carbon and nitrogen stores and fluxes in a Norway spruce (*Picea abies* (L.) Karst.) stand after 33 years.** Forest Ecology and Management. 256: 201-208.

This study presents results of a long-term field experiment to evaluate the effects of thinning treatments on a then 22-year-old *Picea abies* stand in Norway. The stand was thinned from 3,190 to 2,070, 1,100, and 820 trees/ha, respectively; this treatment was replicated three times to create four plots of each treatment. Results from 32-33 years after thinning indicate a significant decrease ($p<.05$) in standing biomass C storage (trunk, bark, living and dead branches, stumps, and coarse and fine roots) for the N1100 stand and the N870 stand (22 and 27 percent decrease, respectively) compared to the N2070 treatment (difference between the N1100 and N870 stands was not significant). Thinning generally is thought to increase volume production of remaining trees in the stand, but this was not true in this experiment, the results of which correspond to similar findings in other experiments in Norway. Differences in ground vegetation between thinning treatments were not significant ($p>.05$), but there was large variation between plots. There was a negative correlation between standing volume and C storage in ground vegetation. Litterfall C was lower on more intensively thinned plots but the difference was not significant. The study concludes that 32-33 years is likely too short a period in which to detect differences in soil C pools based on thinning treatments. However, longer time periods may not reveal greater differences given the variability and sampling scheme.

33. Shan, J.; Morris, L.A.; Hendrick, R.L. 2001. **The effects of management on soil and plant carbon sequestration in slash pine plantations.** Journal of Applied Ecology. 38: 932-941.

This study examines the effects of three management treatments (fertilization, understory elimination, and fertilization plus understory elimination) and a control on aboveground and soil biomass of a 17-year-old *Pinus elliottii* stand in northern Florida. All treatments significantly ($p<.05$) increased tree biomass and thus tree C (stems, branches, and needles). Eliminating the understory increases forest floor biomass, but results in lower soil C storage for all three treatments (p<.05), though not all differences among treatments were significant. Extensive C pool tables are included in this publication. This study concludes that intensive management can increase sequestration in aboveground biomass and subsequent wood products, though soil C storage remains unaffected or may decrease in some cases.

34. Smithwick, E.A.H.; Harmon, M.E.; Remillard, S.M.; Acker, S.A.; Franklin, J.F. 2002. **Potential upper bounds of carbon stores in forests of the Pacific Northwest.** Ecological Applications. 12: 1303-1317.

Old growth forests are significant C stores particularly in the highly productive Pacific Northwest. This study examines 43 old growth stands (150-1200 years old, without a major disturbance) in five distinct biomes to determine the upper bound of C sequestration in the region, absent anthropogenic and natural disturbances. Coastal Oregon stands represent the upper bound and can accumulate stocks of up to 1,127 Mg C/ha (total ecosystem C); average area-weighted total ecosystem C for the Pacific Northwest was 671 Mg C/ha to a soil depth of 1.0 m, and 640 Mg C/ha to a soil depth of 50 cm.

35. Sullivan, B.W.; Kolb, T.E.; Hart, S.C.; Kaye, J.P.; Dore, S.; Montes-Helu, M. 2008. **Thinning reduces soil carbon dioxide but not methane flux from southwestern U.S.A. ponderosa pine forests.** Forest Ecology and Management. 255: 4047-4055.

This study examines the effects of a thinning treatment on CO_2 and methane fluxes, forest-floor and understory biomass, and soil temperature, water content, and microbial biomass C in a *Pinus ponderosa* stand in Arizona. Thinning reduces soil CO_2 efflux immediately after treatment but has no effect on methane oxidation rates during the post-treatment months measured. Forest-floor mass at each site was statistically similar (p=.899) 2 years after thinning; aboveground understory plant biomass was significantly greater (p<.05) at the thinned site after 1 year.

36. Van Miegroet, H.; Moore, P.T.; Tewksbury, C.E.; Nicholas, N.S. 2007. **Carbon sources and sinks in high-elevation spruce-fir forests of the Southeastern U.S.** Forest Ecology and Management. 238: 249-260.

The study measures C pools and fluxes in a mature high-elevation *Picea rubens-Abies fraser* forest in the Great Smoky Mountains National Park, on the border of North Carolina/ Tennessee. Although aboveground spruce C pools are highly variable, average C storage is estimated at 403 Mg C/ha. More than half of this storage was in soils whereas dead wood (mostly fir) accounted for as much as 15 percent of ecosystem C. The study estimates mean live tree sequestration (2.7 Mg C/ha/yr), dead wood release (1.6 Mg C/ha/yr) and net soil efflux (1-1.45 Mg C/ha/yr), depending on assumptions, and concludes that the system is near carbon-neutral.

37. Vesterdal, L.; Rosenqvist, L.; Salm, C.; Hansen,K; Groenenberg, B.J.; Johansson, M.B. 2007. **Chapter 2: Carbon sequestration in soil and biomass following afforestation: experiences from oak and Norway spruce chronosequences in Denmark, Sweden and the Netherlands.** In: Heil, G.W.; Muys, B.; Hansen, K., eds. Environmental effects of afforestation in North- Western Europe. Dordrecht, The Netherlands: Springer: 19-51.

This study examines C pools associated with six common European tree species 30 years after afforestation. There were pronounced differences in the forest-floor C pool and, in some cases, differences in the soil C pool. There were no major difference in the combined forest-floor and mineral-soil layers, though species with smaller forest-floor C pools tended to have larger soil C pools. There were differences in storage profiles (but not necessarily total storage) of C, N, and C/N ratios within the five deciduous tree species. Forest-floor pools were greatest for *Picea abies*, followed by *Fagus* spp. and *Quercus* spp.; *Fraxinus*, *Tilia*, and *Acer* had the least C accumulation in forest floor pools.

38. Wang, C.; Bond-Lamberty, B.; Gower, S.T. 2003. **Carbon distribution of a well- and poorly-drained black spruce fire chronosequence.** Global Change Biology. 9: 1066-1079.

The study examines the effects of soil drainage on carbon accumulation and allocation across a *Picea mariana* fire-influenced chronosequence in Manitoba, Canada. Two stand conditions (dry and wet) are compared across seven different stands. Stands originated after stand-replacing wildfires in 1850, 1930, 1964, 1981, 1995, and 1998. Results show significantly greater ($p<.05$) overstory biomass, MAI, woody debris mass, and litterfall for the dry stands; the wet stands have significantly greater ($p<.05$) bryophyte, understory, and forest floor C pools. Total aboveground biomass for dry stands ranges from 0.6-71.7 Mg C/ha (depending on age), but this is significantly greater ($p<.05$) than the equivalent range for wet stands (0.3-31.2 Mg C/ha). This is within the range of other studies of boreal *Picea mariana* stands (115-year-old *P. mariana* stands at BOREAS study sites have biomass C pools of 70.6 Mg C/ha in northern dry areas, and 67.6 /17.3 Mg C/ha in southern dry/wet areas, respectively). Biomass C pool estimates of *P. mariana* stands in western Canada range from 5.0-54.0 Mg C/ha; world *P. mariana* estimates range from 7.9-118.7 Mg C/ha. Total ecosystem C accumulation for the oldest stands (151 years old) is 533.5 Mg C/ha for dry stands and 470.4 Mg C/ha for wet stands. The importance of soil drainage and age structure on temporal and spatial C distribution in these stands must be taken into account in large-scale C budget modeling.

II. Models

39. Akselsson, C.; Westling, O.; Sverdrup, H.; Gundersen, P. 2007. **Nutrient and carbon budgets in forest soils as decision support in sustainable forest management.** Forest Ecology and Management. 238: 167-174.

This study compares the potential for climate change mitigation in Swedish forests from C sequestration in forest ecosystems vs. fossil fuel substitution from bioenergy derived from whole-tree harvesting. Authors argue that sequestration in forest ecosystems is a method of delaying emissions, and therefore not a sustainable solution. Results indicate that biofuel from whole-tree harvesting can substitute for 3.6 million metric tons of oil/yr, which equates to emissions savings of 11 million tons CO_2e/yr. Sequestration in forest soils currently yields a sink of 100 kg C/ha/yr, or 2 million tons C/yr (7.34 million tons CO_2e), but the study warns that this sink is not sustainable, and long-term capacity is not substantial. Whole-tree harvesting would lead to net losses in nutrients (specifically N and base cations), and compensatory fertilization would be required.

40. Alig, R.J.; Adams, D.M.; McCarl, B.A. 2002. **Projecting impacts of global climate change on the U.S. forest and agriculture sectors and carbon budgets.** Forest Ecology and Management. 169: 3-14.

This study uses the FASOM model and finds that impacts to the United States forest sector by climate change are relatively small. Results agree with those of other studies, suggesting that currently in the United States, existing variation and yields exceed variations caused by climate change. The model assumes an inelastic demand for wood products and predicts changes in United States forest carbon inventory ranging from +0.1 to -0.2 percent through 2020, and -1.0 percent to -1.7 percent through 2050, due to higher harvesting levels. The model does not consider climate feedback and changes to disturbances and assumes that timber production will "migrate" from north to south according to climate-induced productivity changes.

41. Backéus, S.; Wikström, P.; Lämås, T. 2005. **A model for regional analysis of carbon sequestration and timber production.** Forest Ecology and Management. 216: 28-40.

This study presents a local/regional optimization model (created using linear program formulation that is considered a mixture of model 1 and model 2 formulation for linear modeling) that incorporates economic values for timber production and C sequestration (but does not incorporate effects of climate change). The model was developed using individual tree- and stand-level data from the Swedish National Forest Inventory and uses linear programming to develop optimal stand management solutions based on C prices. Harvesting generally decreases and landscape C storage increases as C prices increase; total storage for 3.2 Mha of boreal forest in Sweden ranges from 1.48-2.05 Mt C/yr.

42. Baral, A.; Guha, G.S. 2004. **Trees for carbon sequestration or fossil fuel substitution: the issue of cost vs. carbon benefit.** Biomass and Bioenergy. 27: 41-55.

This study compares the potential for mitigation through afforestation without harvest vis-à-vis bioenergy using growth conditions and species typical of the southeastern United States. Differences over a 100-year period are significant: biomass-based BIG/STIG (biomass-integrated gasified/steam-injected gas turbine substituting) technology, if commercially available, cost-effective, and substituted for coal-fired steam-electric power, could result in an additional C benefit of 3.03 Mg C/ha over traditional afforestation without harvest. This study notes that findings should be considered theoretical until technology is proven as commercially viable and cost effective.

43. Bateman, I.J.; Lovett, A.A. 2000. **Estimating and valuing the carbon sequestered in softwood and hardwood trees, timber products and forest soils in Wales.** Journal of Environmental Management. 60: 301-323.

This study stresses the importance of full C accounting in creating scientifically sound policy and states that C in aboveground biomass, wood products and waste, and soils must be considered in any study of C flux. The model demonstrates that economic drivers, specifically in the form of discount rates, exert the most influence on total C storage and emission values (lower discount rates increase flux). Other factors that influence C flux, in descending order of importance, are forest management, timber growth rates, and species selection. Planting on peat soils can stimulate large C releases that outweigh C sequestered in live wood.

44. Battaglia, M.; Sands, P.; White, D.; Mummery, D. 2004. **CABALA: a linked carbon, water and nitrogen model of forest growth for silvicultural decision support.** Forest Ecology and Management. 193: 251-282.

This paper develops and validates a robust, generally applicable, and accurate silvicultural decision-support system (model) that links C, water, and N flows through the atmosphere, biomass, and soils. A key difference between CABALA and other models is that it links aboveground and belowground processes. The process functions included in CABALA also provide a framework for localizing the model, which is generally suitable for decadal-scale studies, but perhaps not for long-term sustainability studies.

45. Bergh, J.; Freeman, M.; Sigurdsson, B.; Kellomäki, S.; Laitinen, K.; Niinistö, S.; Peltola, H.; Linder, S. 2003. **Modeling the short-term effects of climate change on the productivity of selected tree species in Nordic countries.** Forest Ecology and Management. 183: 327-340.

Low primary productivity is characteristic of boreal forests, but increasing CO_2 concentrations and temperatures associated with climate change could influence productivity and future boreal C balance. The study reports on simulations on coniferous (*Pinus sylvestris, Picea abies*) and deciduous broadleaf (*Fagus sylvatica, Populus trichocarpa*), stands across a climatic gradient in northern Europe. Scenarios modeled were control (0 °C and 350 ppm), +2 °C and 350 ppm, +4 °C and 350 ppm, 700 ppm, +2 °C and 700 ppm, +4 °C and 700 ppm. Coniferous species are responsive to increased temperatures, which induced an earlier start to photosynthetic capacity recovery and increased the length of spring recovery. The +2 °C and +4 °C scenarios increased respiration rates throughout the year for all sites and species, but also generally increased water demands and water deficit, which in turn, reduced NPP in some scenarios. NPP of *P. sylvestris* and *P. abies* increased by 24-37 percent in the +4 °C scenario. Elevated CO_2 scenarios increased NPP for coniferous species on some sites by 25-40 percent and increased NPP of Denmark beech sites by 58 percent, primarily by improving water use efficiency. This paper stresses the need for research on low-temperature effects and soil-nutrient feedback mechanisms (increased growth naturally leads to increased nutrient demand) to avoid unrealistic predictions of C gains or climate change effects in boreal forest ecosystems.

46. Bond-Lamberty, B.; Peckham, S.D.; Ahl, D.E.; Gower, S.T. 2007. **Fire as the dominant driver of central Canadian boreal forest carbon balance.** Nature. 450: 89-92.

This study employed the Biome-BGC process model to study the effects of changing environmental conditions (changing climate, increased CO_2 concentrations, fire disturbances) on NPP, net biome production, vegetation competition, and C balance on 100 Mha of Canadian boreal forest dominated by *Picea mariana* and *Populus tremuloides.* Fire disturbance has increased concentrations of deciduous trees at the expense of coniferous trees, and that the C balance of the region from 1948-2005 has been driven primarily by fire disturbance. The authors conclude that climate-related changes have been driven primarily by increased fire frequency, which has affected the variability but not the mean of the region's C balance over time, and that the region has not yet experienced direct ecophysiological changes driven by climate change.

47. Böttcher, H.; Freibauer, A.; Obersteiner, M.; Schulze, E.-D. 2008. **Uncertainty analysis of climate change mitigation options in the forestry sector using a generic carbon budget model.** Ecological Modelling. 213: 45-62.

This study presents a generic dynamic forestry model (FORMICA) that can be used to model forest C dynamics and sink potential of landscape forest C pools, as well as from harvested wood products and fossil fuel substitution.

48. Brack, C.L. 2002. **Pollution mitigation and carbon sequestration by an urban forest.** Environmental Pollution. 116: 195-200.

This paper delivers a case study that enumerates and economically quantifies the benefits of an urban forest to the southeast Australian city of Canberra. The study uses a model to predict C sequestration by 400,000 urban trees and converts that figure into a Kyoto-commitment-driven dollar value over 4 years (U.S. $300,000) and demonstrates that the majority of the value of urban trees derives from energy savings, pollution amelioration, and hydrology amelioration (estimated at U.S. $20-67 million for the city of Canberra from 2008-2012).

49. Bravo, F.; Bravo-Oviedo, A.; Diaz-Balteiro, L. 2008. **Carbon sequestration in Spanish Mediterranean forests under two management alternatives: a modeling approach.** European Journal of Forest Research. 127: 225-234.

This study examines C sequestration and associated economic impact on two different even-aged management alternatives (long and short rotation) on two simulated stands. One stand was composed of *Pinus sylvestris* and the other of *Pinus pinaster*; both include numerous site quality indexes. In each case, the study simulates a clear cut followed by natural regeneration, precommercial thinning, and a low thinning regimen to achieve stand densities of 1,600 trees/ha in *P. sylvestris* and to 1,500 trees/ha in *P. pinaster*. Increasing rotation length on poor quality sites allows trees to store as much C as shorter rotations on high quality sites, and combined longer rotations and gains in C revenue can make poor quality sites profitable while creating a positive impact on biodiversity. In all circumstances, increasing rotation length increases the proportion of C stock in the final harvest relative to total fixed C.

50. Briceño-Elizondo, E.; Garcia-Gonzalo, J.; Peltola, H.; Kellomäki, S. 2006. **Carbon stocks and timber yield in two boreal forest ecosystems under current and changing climatic conditions subjected to varying management regimes.** Environmental Science & Policy. 9: 237-252.

The study uses a process-based ecosystem model (FINNFOR) to determine the impact of thinning regimes and changing climate on forest ecosystem C stocks. Simulations were performed over a 100-year period for *Pinus sylvestris, Picea abies*, and *Betula pendula* in Finnish boreal forests. Across each of three climate scenarios (one current and two projection models: HadCM2 and ECHAM4), all three species demonstrated maximum C sequestration when traditional thinning regimens were most drastically altered to allow for a 30 percent increase in forest stock. The findings demonstrate and validate the hypothesis that C stocks in forest ecosystems can be increased by applying a proper thinning regimen without increasing rotation length or experiencing losses in timber production. This study recommends a "no regrets" option of increasing thinning thresholds, thereby increasing total stocks and carbon sequestered.

51. Briceño-Elizondo, E.; Garcia-Gonzalo, J.; Peltola, H.; Matala, J.; Kellomäki, S. 2006. **Sensitivity of growth of Scots pine, Norway spruce and silver birch to climate change and forest management in boreal conditions.** Forest Ecology and Management. 232: 152-167.

Authors use a process-based ecosystem model (FINNFOR) linking C, N, energy, and water flows in trees and soils to examine climate change effects on tree growth and timber production for three species in northern and southern Finnish boreal forests. Thinning regimes that were less intensive than the traditional thinning level under two projected climate change scenarios resulted in universal increases in tree growth and timber yield compared to a baseline climate scenario. Gains generally were larger in the north, where forests benefit more from warmer temperatures.

52. Briceño-Elizondo, E.; Jäger, D.; Lexer, M.J.; Garcia-Gonzalo, J.; Peltola, H.; Kellomäki, S. 2008. **Multi-criteria evaluation of multi-purpose stand treatment programmes for Finnish boreal forests under changing climate.** Ecological Indicators. 8: 26-45.

This study uses MCA within the FINNFOR model to demonstrate that higher stocking levels, in the form of unthinned stands or maximally increased thinning thresholds (30 percent increase in upper and lower limits of basal area), result in greater utility compared to a BT treatment program; BT (0,0) is the standard/recommended guideline for thinning in Finland. The study emphasizes the importance of reconsidering current forest management techniques (specifically thinning regimes) in light of changing climate scenarios, to maximize C storage and timber yield.

53. Chen, W.; Chen, J.M.; Price, D.T.; Cihlar, J.; Liu, J. 2000. **Carbon offset potentials of four alternative forest management strategies in Canada: A simulation study.** Mitigation and Adaptation Strategies for Global Change. 5: 143-169.

This study uses an integrated terrestrial ecosystem C budget model (InTEC) to assess the mitigation potential of four alternative forest management scenarios in Canada. In order of greatest benefit: amendment application (5 kg N/ha/yr) on 125m ha of semi-mature boreal forests (58 Tg C/yr); promptly reforesting disturbed land (57 Tg C/yr); increasing harvest levels by 20 percent to create bioenergy to offset fossil fuel use (11 Tg C/yr); and afforesting all 7.2 million ha of marginal agricultural land (8 Tg C/yr). This study presents experimental evidence to support theoretical gains from N application, though other studies show that the response of forests to fertilization remains highly variable.

54. Chladná, Z. 2007. **Determination of optimal rotation period under stochastic wood and carbon prices.** Forest Policy and Economics. 9: 1031-1045.

This publication presents a model to optimize forest management. The study demonstrates that optimal rotation length is closely connected to timber and C prices and price behavior, discount rate, and whether the forest landowner is responsible for C emissions at harvest.

55. Creedy, J.; Wurzbacher, A.D. 2001. **The economic value of a forested catchment with timber, water and carbon sequestration benefits.** Ecological Economics. 38: 71-83.

This study develops a mathematical model to optimize the net present value of timber, water, and aboveground sequestration benefits for a forested catchment in Victoria, Australia. Allowing for various carbon price and discount rate inputs, the model demonstrates that accounting for nontimber benefits can significantly lengthen optimal rotation length.

56. De Jong, B.H.; Masera, O.; Olguín, M.; Martínez, R. 2007. **Greenhouse gas mitigation potential of combining forest management and**

bioenergy substitution: A case study from Central Highlands of Michoacan, Mexico. Forest Ecology and Management. 242: 398-411.

The study employs the CO_2FIX v 3.1 modeling software to determine the optimal strategy for 11,000 ha of native predominantly *Pinus-Quercus* forests in central Mexico. The combination "oak conservation + bioenergy" strategy provides the most C gain 21.6-42.9 tons C/ha. The oak conservation strategy stops yielding C gains (8.2 -19.3 tons C/ha) after about 40 years, while the combination strategy yields gains of 1.36 tons C/ha/yr continuously.

57. De Jong, B.H.J.; Tipper, R.; Montoya-Gómez, G. 2000. **An economic analysis of the potential for carbon sequestration by forests: evidence from southern Mexico.** Ecological Economics. 33: 313-327.

This study uses economic modeling to determine the potential for enhanced mitigation through improved forest management and other techniques on 600,000 ha in southern Mexico. An additional 63 Mg C/ha can be sequestered at a cost of U.S. $15/ton C ($15/Mg C). Roughly 80 percent of these gains are directly related to improved forest management. This study also emphasizes the importance of a baseline in determining extra C stored and the cost-effectiveness of forest-based C storage.

58. Dean, C.; Roxburgh, S.; Mackey, B.G. 2004. **Forecasting landscape-level carbon sequestration using gridded, spatially adjusted tree growth.** Forest Ecology and Management. 194: 109-129.

This publication reports on a model (CAR4D) to scale up C sequestration forecasts to the landscape level while accounting for nonlinearities, environmental variability, and temporal and spatial scaling issues that often lead to inaccuracies in landscape-level forecasts. C storage in *Eucalyptus regnans* stands peaks about 130 years after establishment, at which point the forest becomes a net source. A C bank can be maintained at a stable level by mixing old and young stands across a landscape. A wider profile of forest stand ages results in a more stable C bank forecast. Results also indicate when and how models can be improved through additional collection of field data.

59. Díaz-Balteiro, L.; Romero, C. 2003. **Forest management optimization models when carbon captured is considered: a goal programming approach.** Forest Ecology and Management. 174: 447-457.

This study presents a model that incorporates C sequestration objectives into optimal forest management and highlights some inherent tradeoffs, including unacceptable results that derive from a singular focus on optimizing any one criterion. It includes an optimization case study from a *Pinus sylvestris* dominated forest in north-central Spain.

60. Environmental Protection Agency. 2005. **Greenhouse gas mitigation potential in U.S. forestry and agriculture.** Washington, DC: U.S. Environmental Protection Agency. 154 p.

Although this study employs a comprehensive and dynamic model (Forest and Agriculture Sector Optimization Model with Greenhouse Gases—FASOMGHG) and thus warrants categorization in this section, the study could easily fit into section 4 (Literature reviews and meta-analyses) because of its comprehensive, meta-analytical nature. The study integrates biological and economic data to demonstrate that the United States forestry and agricultural sectors together constitute a major C sink (~830 Tg C/yr), over 90 percent of which is on forest land. Sink strength on forest land compensates for and outweighs releases due to wildfires, harvests, and conversions to nonforest use. Economic modeling demonstrates the possibility for increased terrestrial storage given adequate GHG prices and certain assumptions about landowner behavior. The study suggests that at lower price ranges (less than or equal to $5/ton$CO_2$e), agricultural soil sequestration and forest management for increased C storage are "dominant mitigation strategies" and that afforestation becomes the dominant strategy at higher (>$15/ton$CO_2$e) prices. Data from the past several years generated by the Chicago Climate Exchange and over-the-counter carbon markets show that $5/ton$CO_2$e has barely been sufficient to cover costs, stimulate interest, and dissipate owner reluctance/uncertainty about engaging in markets and/or encumbering his or her land with long-term commitments.

61. Eriksson, E.; Gillespie, A.R.; Gustavsson, L.; Langvall, O.; Olsson, M.; Sathre, R.; Stendahl, J. 2007. **Integrated carbon analysis of forest management practices and wood substitution.** Canadian Journal of Forest Research. 37: 671-681.

This study examines the effects of three forest management scenarios (traditional, intensive management, and intensive fertilization), three slash-management practices (no removal, removal, and removal with stumps), two forest-product uses (construction material and biofuel), and two reference fossil fuels (coal and natural gas) on the total C balance of a *Picea abies* forest. This study combines a forest-growth, forest-soil, and product-use model to represent the system, and finds that forest-product usage has much greater impact on the total carbon budget than changes in accumulation in biomass and soils due to various types of management. The greatest overall C gains are achieved through a combination strategy of stand fertilization, harvest with slash and stumps removed, and timber converted into long-term construction wood products and then substituted for coal-based fuel after its useful life as construction materials. This strategy generated a savings of more than 3 Mg C/ha/yr above a baseline (excludes fertilization or stump removal, and substitutes wood products for natural gas). Results support the idea that intensively managed forests can significantly mitigate climate change and that most of the benefit derives from substituting wood for more C-intensive products.

62. Felzer, B; Kicklighter, D.; Melillo, J.; Wang, C.; Zhuang, Q.; Prinn, R. 2004. **Effects of ozone on net primary production and carbon sequestration in the conterminous United States using a biogeochemistry model.** Tellus B. 56: 230-248.

This study evaluates the effects of ozone on NPP and terrestrial C sequestration in the coterminous United States using the Terrestrial Ecosystem Model. It estimates a 2.6-6.8 percent mean reduction in annual NPP from ozone which translated into a reduction in United States forest C sequestration of 18-38 Tg C/yr since the 1950s.

63. Fujikake, I. 2007. **Selection of tree species for plantations in Japan.** Forest Policy and Economics. 9: 811-821.

This study examines the effect of economic factors on decisions about which species to plant in Japanese plantation forests. Changes in stumpage prices and forestry wages have been the primary drivers in a switch from Sugi to Hinoki. Hinoki forests are slower growing, generally allow for less understory development, and have faster litter decomposition and greater soil erosion rates, making them less robust C sinks. If forest C and other ecosystem benefits were quantified and valued economically, managers of plantation forests could make long term decisions that are more ecologically sound.

64. Fürstenau, C.; Badeck, F.; Lasch, P.; Lexer, M.; Lindner, M.; Mohr, P.; Suckow, F. 2007. **Multiple-use forest management in consideration of climate change and the interests of stakeholder groups.** European Journal of Forest Research. 126: 225-239.

The MCA method is paired with the 4C (Forest Ecosystems in a Changing Environment) growth model to determine the utility of a range of forest management scenarios under a variety of climate conditions to three separate stakeholder groups (private forest owner, public forest manager, and environmental organization). The greatest overall increase in total C sequestration was greatest for the “no management/conservation strategy”, even when C in soil and long-term wood products from other scenarios was considered. However, the utility of this management scenario was low for all but the environmental organization, and this one-time increase in C storage was vulnerable to release through climate-related or other disturbances. Also, the MCA method is designed to maximize the utility of adaptive management decisions to various stakeholder groups in an era of uncertain climate changes, so C sequestration is only one component of a number of functions (e.g., timber yield, groundwater recharge, and biodiversity factors) that must be considered. Outcomes depend entirely on specific circumstances and local conditions.

65. Garcia-Quijano, J.F.; Deckmyn, G.; Ceulemans, R.; Van Orshoven, J.; Muys, B. 2008. **Scaling from stand to landscape scale of climate change mitigation by afforestation and forest management: A modeling approach.** Climatic Change. 86: 397-424.

A process-based model (SECRETS) designed to overcome stand-to-landscape scaling problems is linked with a C accounting model (GORCAM) to fully consider the carbon implications and effects of forest management, afforestation, and bioenergy production. The model accurately predicts C stocks in various pools for current environmental conditions, but comparison with field data suggests that accurate predictions under changing climate scenarios require greater functionality. Results suggest that under current climate conditions, the best scenario for both sequestering and avoiding emissions involves a combination of conservation of old-growth reserves, use of existing multifunctional forest, and “short rotation coppice” for bioenergy production. Soil C and litter pools present a modeling challenge and related inaccuracies in these pools may amplify uncertainties.

66. Garcia-Gonzalo, J.; Peltola, H.; Zubizarreta Gerendiain, A.; Kellomäki, S. 2007. **Impacts of forest landscape structure and management on timber production and carbon stocks in the boreal forest ecosystem under changing climate.** Forest Ecology and Management. 241: 243-257.

The study uses a process-based model (FINNFOR) to determine the C sequestration sensitivity of a boreal forest ecosystem to different age class distributions and thinning regimes. The effects of the HadCM2 climate scenario (increased temperature, precipitation, and atmospheric CO_2 concentration) increased *de facto* forest productivity (total aboveground stock increased while soil C decreased due to higher respiration, but the overall effect was a net gain in ecosystem C). Unthinned stands result in maximum ecosystem sequestration. Although thinning resulted in ecosystem C losses, a shift in thinning from BT (0,0) to BT (30, 30), or a 30 percent increase in the thinning threshold that allowed for higher stocking densities, resulted in notable C benefits (13 Mg C/ha) over the 100-year simulation period under both current and future climate scenarios. Initial age class distribution generally did not result in substantial differences in forest C stock over 100 years.

67. Gutrich, J.; Howarth, R.B. 2007. **Carbon sequestration and the optimal management of New Hampshire timber stands.** Ecological Economics. 62: 441-450.

A model is used to examine decisions related to harvesting/rotation length New Hampshire in light of the economic tradeoffs between timber and C sequestration values. Results show that optimal rotation length is extended from 16 to 133 years depending on forest type when forest C storage is valued between $25-75 per ton C, respectively. As a second scenario, the study cites the UNFCCC goal to stabilize atmospheric CO_2 concentrations at a level that would avoid catastrophic harm. At 580 ppm, Howarth (2001) estimates C prices to be $227-570/ metric ton C; at such prices, the study estimates that optimal rotation length of stands in New Hampshire would range from 222-391 years. Partial harvesting rather than clearcut-harvesting provides “high net benefits under a variety of circumstances.” The model only incorporates optimal management at the stand level, and does not consider regional-level impacts (leakage, etc.); model valuation of timber could be improved and may not represent conditions on a specific timber stand.

68. Harmon, M.; Marks, P. 2002. **Effects of silvicultural practices on carbon stores in Douglas-fir-western hemlock forests in the Pacific Northwest, USA: results from a simulation model.** Canadian Journal of Forest Research. 32: 863-877.

This study uses the model STANDCARB to simulate the effects of five treatments on C stores in stands of *Pseudotsuga menziessii* and *Tsuga heterophylla* in Oregon, and found that three factors in particular (detritus removed by slash burning, amount of mass harvested, and rotation length, listed in order of decreasing importance) greatly affect landscape carbon stores. There was a notable decline in landscape C following conversion/disturbance/management of old-growth forests. Agricultural land stored only 15 percent of total C capacity whereas "forests protected from fire" stored 93 percent of total capacity. Therefore, converting agricultural land to forest increased landscape C stores.

69. Hennigar, C.R.; MacLean, D.A.; Amos-Binks, L.J. 2008. **A novel approach to optimize management strategies for carbon stored in both forests and wood products.** Forest Ecology and Management. 256: 786-797.

An analysis is presented which demonstrates the importance of full C accounting when attempting to optimize mitigation. It evaluates four separate objectives for a modeled forest in New Brunswick, Canada, (using Remsoft Spatial Planning System) and finds that a scenario to maximize carbon in forest + products + substitution resulted in storage of 0.228 Mg C/ha/yr; a scenario to maximize harvest resulted in storage rates of 0.126 Mg C/ha/yr.

70. Huang, C.-H.; Kronrad, G.D. 2001. **The cost of sequestering carbon on private forest lands.** Forest Policy and Economics. 2: 133-142.

This study uses the forest stand simulator model PTAEDA2 to analyze the costs of C sequestration of *Pinus taeda*, comparing the SEV of biologically vs. economically optimal rotation lengths. The former maximizes C stored on the forest and in long-lived wood products; the latter maximizes the economic value of sawtimber. The objective was to determine the maximum mean annual increment of these two goals. Results show a difference of as much as 0.79 Mg C/ha. Depending on site quality class (50, 60, 70, 80, 90) and the discount rate used, the price per additional ton of sequestered C on forest land ranged from \$0.84 to \$72.79/ha. This is the price that one would need to pay forest managers to incentivize them to switch from economically to C-optimal rotation lengths). The sequestration potential and associated price for incentivizing landowners to restock barren land was 1.03-3.77 Mg C/ha and \$0.74 - \$27.32/ha, respectively. The cost of sequestering an additional ton of C intensively managed land was \$4.18 - \$181.27/ha. Findings assumed an initial age of 25 years, maximum rotation of 60 years, 0-3 thinnings (first thinning would be row and from below; subsequent thinnings, if any, would be from below) and thinning intensities of 20, 25, 30, or 35 percent of basal area removed.

71. Hurteau, M.D.; Koch, G.W.; Hungate, B.A. 2008. **Carbon protection and fire risk reduction: toward a full accounting of forest carbon offsets.** Frontiers in Ecology and the Environment. 6: 493-498.

This study quantifies the CO_2 released from the four largest U.S. wildfires in 2002 (Rodeo–Chediski, Hayman, Biscuit, and McNally) in light of forest management practices that might mitigate or reduce the likelihood of such large releases. These fires charred 508,000 ha, 92,000 of which were burned severely. Previous studies and models were used to estimate C storage for unmanaged forests typical of those that burned, and derive estimates of C storage per tree component and per hectare. Models and combustion factors were also used to estimate post-fire C storage for burned thinned and unthinned stands. Results showed that 4.2-6.1 Mt CO_2e were released in fires from unthinned stands. Thinning these stands would have released 3.9 Mt CO_2e but reduced live-tree fire emissions by 0.07-0.3 Mt CO_2e.

72. Hynynen, J.; Ahtikoski, A.; Siitonen, J.; Sievänen, R.; Liski, J. 2005. **Applying the MOTTI simulator to analyze the effects of alternative management schedules on timber and non-timber production.** Forest Ecology and Management. 207: 5-18.

This MOTTI stand model was used to simulate the effects of three stand management alternatives on a 35-year old *Picea abies*-dominated stand in southern Finland. Management alternatives included a pure spruce stand with commercial thinning (x2) and harvest (at age 70) with the goal of maximizing wood production, a mixed stand with commercial thinning (x2) and harvest (at age 70) with a goal of enhancing biodiversity, and an unmanaged stand that was not treated. Over the 70-year simulation period, total soil C pool was roughly the same in pure and mixed stands and only slightly higher in no management stands. The tree C pool also was about the same in pure and mixed stands, but much higher in unmanaged stands (about 215 for pure/mixed vs. 270 Mg C/ha). Biodiversity was 50 and 88 percent higher in mixed and unmanaged stands, respectively. These results based on underlying assumptions and thus subject to errors and uncertainties. Also, the biodiversity findings may not be applicable to all boreal forest ecosystems.

73. Janisch, J.; Harmon, M. 2002. **Successional changes in live and dead wood carbon stores: implications for net ecosystem productivity.** Tree Physiology. 22:77-89.

This study uses data from a 500-year-old chronosequence in the Pacific Northwest to model the effects of forest management on the woody component of NEP, specifically C recovery horizons following management/disturbance. Transitioning from old growth to younger managed forest stands results in significant C losses that are not recovered for many decades. Eighty-year-old regenerating stands stored half the C of 500-year old growth forests. The study notes that such scientific findings must be carefully considered when designing mitigation projects to avoid adverse effects and net releases of C to the atmosphere.

74. Jayawickrama, K.J.S. 2001. **Potential genetic gains for carbon sequestration: A preliminary study on radiate pine plantations in New Zealand.** Forest Ecology and Management. 152: 313-322.

This study reports on modeled C gains for *Pinus radiata* plantations in New Zealand as a result of two different levels of genetic improvement (selecting the best 50 of 500 parents, and the best 10 of 1,000 parents). These C gains were mapped over different geographical regions and management strategies over a rotation length of 28 years (which included two thinnings and one pruning for all locations). Modeled long-term average gains are as much as 22 percent for the more stringent improvement (best 10 of 1000 parents). Increases ranged from 19.0 to 29.3 Mg C/ha depending upon site and using a standard (direct saw log) management regime. For the same site, the 28-year gains were highest when a plant-and-leave "low-cost" management approach was used.

75. Jiang, H.; Apps, M.J.; Peng, C.; Zhang, Y.; Liu, J. 2002. **Modelling the influence of harvesting on Chinese boreal forest carbon dynamics.** Forest Ecology and Management. 169: 65-82.

This paper examines modeled effects of three harvest/disturbance scenarios (no biomass removal, conventional harvesting, whole-tree harvesting) over 100-year rotations, and the same scenarios but with rotation lengths of 30, 50, 100, 200, or 400 years on *Larix* (dominant)-*Betula*-*Pinus*-*Quercus* boreal forests in China. The "no biomass removal" scenario resulted in C gains of 303 and 330 Mg C/ha over conventional and whole-tree harvesting, respectively, over 100 years. Chinese boreal forests generally are more productive and contain more biomass than North American or Russian boreal forests.

76. Kaipainen, T.; Liski, J.; Pusssinen, A.; Karjalainen, T. 2004. **Managing carbon sinks by changing rotation length in European forests.** Environmental Science & Policy. 7: 205-219.

The study uses the CO_2FIX model to determine the effects and magnitude of increased rotation lengths on European forest C pools to determine how to achieve the largest eligible C sink for Kyoto Protocol-related commitments. Increased rotation lengths result in slight decreases in soil C stock in some regions and generally decrease wood product pools (except in U.K. *Picea sitchensis* forests). Depending on forest and site characteristics, rotation lengths should be extended by 20 years on 0.3-5.1 Mha of land to achieve the aforementioned sink.

77. Karjalainen, T.; Pussinen, A.; Liski, J.; Nabuurs, G.-J.; Eggers, T.; Lapveteläinen, T.; Kaipainen, T. 2003. **Scenario analysis of the impacts of forest management and climate change on the European forest sector carbon budget.** Forest Policy and Economics. 5: 141-155.

This study uses scenario analysis to predict the effects of two forest management (business as usual, or BAU; and multifunctional management, which included increased fellings, but also afforestation projects and an emphasis on "nature-oriented management") and two climate scenarios (current climate and HadCM2) on the European forest C budget from 1990-2050. The study encompasses 27 countries and 128.5 Mha. Both management scenarios showed larger total ecosystem gains under HadCM2 than current climate. Because of current climate change effects, current climate scenarios (which were developed several years ago) likely can be dismissed as improbable. The difference between multifunctional and BAU management scenarios in a HadCM2 climate in 2050 was 215 Tg, or about 1.67 Mg/ha. Authors note that uncertainties still exist and could be minimized with more accurate biomass expansion factor and that when scenario analysis is used, more attention should be focused on relative than on absolute scenario differences.

78. Karjalainen, T.; Pussinen, A.; Liski, J.; Nabuurs, G.-J.; Erhard, M.; Eggers, T.; Sonntag, M.; Mohren, G.M.J. 2002. **An approach towards an estimate of the impact of forest management and climate change on the European forest sector carbon budget: Germany as a case study.** Forest Ecology and Management. 162: 87-103.

Process-based models can be used to assess regional climate change impacts, which then can be scaled up to regional/country/continental levels using national forest inventory data along with the European forest information scenario (EFISCEN) model to investigate the effects of different forest management scenarios on C budgets in an era of climate change. Germany is used as a case study.

79. Köhl, M.; Stümer, W.; Kenter, B.; Riedel, T. 2008. **Effect of the estimation of forest management and decay of dead woody material on the reliability of carbon stock and carbon stock changes–A simulation study.** Forest Ecology and Management. 256: 229-236.

IPCC reporting guidelines offer three options for accounting for C stocks in dead wood. This study demonstrates that different approaches to timber utilization and harvesting and assumed decay rates (constant or accelerating) of dead wood greatly affect the amount of C released. When these effects were modeled for a given set of data from Austria, changes in C stock in dead woody material ranged from 3.1-4.4 Mg C/ha/yr.

80. Kraxner, F.; Nilsson, S.; Obersteiner, M. 2003. **Negative emissions from BioEnergy Use, Carbon capture and Sequestration (BECS)—the case of biomass production by sustainable forest management from semi-natural temperate forests.** Biomass and Bioenergy. 24: 285-296.

The study proposes a negative emissions energy system using "semi-natural" temperate forests. It states that "Biomass Energy CO_2 removal through long-term Sequestration" (BECS) provides an insatiable sink for C, thereby reducing atmospheric CO_2 concentrations and risks from nonlinear climate changes. Stem biomass is used to generate energy, while other biomass is left in the forest to preserve nutrient balances and ecosystem integrity. C can be scrubbed and stored during the energy production process; a range of different technology and carbon storage options is cited. C sequestration trajectories in uneven-aged mixed beech-spruce stands are projected under four scenarios: with and without BECS, using various forest management regimes. Thinning and one-time planting with BECS generated the highest average annual sequestration of 2.5 Mg C/ha/yr. Thinning and one-time planting without BECS generated the lowest (0.85 Mg C/ha/yr) average, even lower than the control. Using BECS technology might produce a comparative insatiable and permanent sink of 1.65 Mg C/ha/yr, but the study cites the need for governmental and societal support.

81. Krcmar, E.; Stennes, B.; van Kooten, G.C.; Vertinsky, I. 2001. **Carbon sequestration and land management under uncertainty.** European Journal of Operational Research. 135: 616-629.

The study models potential C uptake on reforested and afforested land, taking into account inherent uncertainties related to forest management.

Uncertainties include: timber yield quantities related to silvicultural practices, climate change effects, and weather; imprecise C sink data; and "vague and changing societal values and preferences," especially with respect to timber harvest and C sequestration levels. Modeled results indicate that parameters and assumptions significantly impact land- use strategies and outcomes. The study concludes by stating that models are useful but cannot determine the best strategy, so the onus of determining inputs and assumptions and determining thresholds for risk lies with decision-makers.

82. Krcmar, E.; van Kooten, G.C.; Vertinsky, I. 2005. **Managing forest and marginal agricultural land for multiple tradeoffs: compromising on economic, carbon and structural diversity objectives.** Ecological Modelling. 185: 451-468.

The study uses "compromise programming" to optimize net present value, nominal and discounted C sequestration totals, and biodiversity structure on a 70/30 percent coniferous/deciduous mixed boreal forest in British Columbia, Canada. The study experiments with balancing or maximizing all or certain of the four objectives and find that significant tradeoffs exist among achieving maximal sequestration, economic benefit, and landscape structural diversity. Namely, maximizing short-term C uptake results in significant compromises in diversity; maintaining a diverse landscape reduces potential economic and C sequestration. Land managers with different risk tolerance levels will utilize different land-use and management strategies.

83. Kurz, W.A.; Dymond, C.C.; Stinson, G.; Rampley, G.J.; Neilson, E.T.; Carroll, A.L.; Ebata, T.; Safranyik, L. 2008. **Mountain pine beetle and forest carbon feedback to climate change.** Nature. 452: 987-990.

The study quantifies the C impacts of a mountain pine beetle outbreak in British Columbia, Canada. The most recent beetle outbreak is an order of magnitude greater than other outbreaks due to an increased area of mature pine stands and climate change related favorable beetle conditions, and has resulted in massive pine mortality and commercial timber losses estimated at 435 million m^3. This CBM-CFS3 model was used to estimate the combined effects of the beetle outbreak, forest fires, and harvesting on south-central British Columbia's forest C balance from 2000-2020 (374,000 km^2 of *Pinus* and *Picea* dominated forests). The cumulative effect caused a net release of 270 Mt, or 0.36 Mg C/ha/yr, thus turning these forests from a small sink to a substantial source. The study concludes that such climate-related disturbances may overwhelm northern forests' ability to sequester and store atmospheric C, and that future large-scale modeling analyses must take this into account.

84. Kurz, W.A.; Stinson, G.; Rampley, G. 2008. **Could increased boreal forest ecosystem productivity offset carbon losses from increased disturbances?** Philosophical Transactions of the Royal Society B: Biological Sciences. 363: 2259-2268.

This study uses the CBM-CFS3 model to compare the anticipated effects of climate change related increases in NPP vis-à-vis the impacts of increased fire and other disturbances over a hypothetical 100,000 ha boreal forest landscape consisting of even-aged stands. The study examines two sets of 81 scenarios; each scenario set combines one of nine growth rate conditions with one of nine disturbance rate conditions. The first set of scenarios features constant decomposition rates; in the second, decomposition rates increase proportionally with growth rates. The study models results to 200 years, though focuses attention on results for the first 50 years. The first set of scenarios suggests that climate-related enhanced C sequestration can compensate for climate-related increased disturbances. However, the second scenario suggests that this will not occur should decomposition rates increase in proportion to increases in growth rate. In the first scenario, a 12 percent increase in growth rates is required to compensate for C losses associated with a 20 percent increase in annual burn area. However, the study concludes that projected increases in disturbance rates are likely to overwhelm growth enhancements such that "the boreal forest biome will act as a net source of C to the atmosphere if climate change brings about the projected increases in disturbance rates."

85. Lasch, P.; Badeck, F.-W.; Suckow, F.; Lindner,M.; Mohr, P. 2005. **Model-based analysis of management alternatives at stand and regional level in Brandenburg (Germany).** Forest Ecology and Management. 207: 59-74.

The study tests and validates a physiologically based model (FORSEE—FOReST Ecosystems in a changing Environment, also known as 4C) parameterized for *Fagus, Picea abies, Pinus sylvestris, Quercus*, and *Betula* using long-term experimental data from a forest in Germany. The model simulated the combined effects of growth, yield, management, and water on C budgets of managed forests over a 50-year horizon without final harvest or stand regeneration under three management scenarios (without thinning but with removal of dead wood; with intensive thinning; and with moderate thinning) and two climate scenarios (current climate and ECHAM4 +1.4 °C change) to determine overall mitigative potential of the forest. Carbon stock assessed includes the sum of total biomass: total C in mineral soil and organic layer, harvested biomass, and deadwood. In both climate scenarios, the no-thinning management option results in greatest total C storage. Simulated climate change has little effect on total C storage (591.5 Tg C/ha total for current vs. 587.8 Tg C/ha total for climate change scenario). Under both climate scenarios, thinning results in less biomass in the forest, more in harvested wood products, and a reduction in soil carbon pools. Increased rotation lengths (160 yrs) results in greatest total carbon storage, but provides suboptimal timber revenues and quality. Projected increases in forest productivity due to longer growing seasons under a changing climate scenario are offset by significantly reduced (-40 percent) percolation rates. There is limited potential for adaptive forest management in this region, which is characterized by dry conditions and poor site quality.

86. Law, B.E.; Thornton, P.E.; Irvine, J.; Anthoni, P.M.; Van Tuyl, S. 2001. **Carbon storage and fluxes in ponderosa pine forests at different developmental stages.** Global Change Biology. 7: 755-777.

The BIOME-BCG model was used to determine NPP, NEP, and C storage by component for two *Pinus ponderosa* stands in central Oregon: a 15-year-old stand in an old growth forest that had been clearcut and allowed to regenerate naturally and an unlogged stand of trees ranging from 50-250 years old. Aboveground tree C storage (bark, branch, stem, foliage) was 5.79 Mg C/ha for the young stand and 107.91 Mg C/ha for the old stand. Fifteen percent of C in the young stand was stored as aboveground live biomass vs. 61 percent for the old stand. The old stand sequesters anywhere from 0.2-1.0 Mg C/ha/yr.

87. Law, B.E.; Sun, O.J.; Campbell, J.; Van Tuyl, S.; Thomton, P.E. 2003. **Changes in carbon storage and fluxes in a chronosequence of ponderosa pine.** Global Change Biology. 9: 510–524.

The BIOME-BCG model was used to determine the NPP, NEP, and C storage in aboveground and soil pools in *Pinus ponderosa* stands of four age classes (initiation, 9-23 years; young, 56-89 years; mature, 95-106 years; and old, 190-316 years) in central Oregon. Total ecosystem C storage increases substantially—most of this increase is in aboveground biomass—until the stands are 150-200 years old, at which point the rate of storage slows but total storage continues to increase. The oldest age class (190-316 years) has a mean storage of 176 Mg C/ha and 85 percent of biomass-based carbon storage is in older (100+ years) stands.

88. Law, B.E.; Turner, D.; Campbell. J.; Sun, O.J.; Van Tuyl, S.; Ritts, W.D.; Cohen, W.B. 2004. **Disturbance and climate effects on carbon stocks and fluxes across Western Oregon USA.** Global Change Biology. 10: 1429-1444.

This study employed both remote and field-based observations with the BIOME-BCG model to estimate total C storage by Oregon forests, which was found to vary considerably by ecoregion and with respect to above/belowground partitioning. Total stock in Oregon is 2765 Tg C (337 Mg C/ha) and mean annual uptake is 13.8 Tg C/yr (1.68 Mg C/ha/yr).

89. Leighty, W.; Hamburg, S.; Caouette, J. 2006. **Effects of management on carbon sequestration in forest biomass in Southeast Alaska.** Ecosystems. 9: 1051-1065.

The Tongass National Forest in Alaska is the largest area of old growth forest in the nation, containing 8 percent of the C found in the forests of the coterminous United States and 0.25 percent of global forest ecosystem C. This study examines the effects of five management scenarios (no harvesting; all lands harvested on a 100-yr rotation; all lands harvested on a 200-yr rotation; administratively available lands harvested on a 100-yr rotation; administratively available lands harvested on a 200-yr rotation) on total atmospheric C flux (all harvesting scenarios include gradual decay of harvested wood products, which were 50/50 sawtimber and pulpwood) from 1995-2095. The model (spatially explicit combined GIS and FIA data model) was also run for a 200-year period from 1995-2195. Results indicate that cessation of all harvesting on available lands results in additional sequestration of 0.03 – 0.25 Mg C/ha/yr. This findings suggest that the Tongass could generate approximately as much revenue ($4-7million/yr) by eliminating harvesting and selling CERs for $20/Mg C (about $5.50 ton/ CO_2e) as it does selling timber ($6.5million/yr in 2001). The policy questions yet to be resolved are: will and should National Forest System lands be eligible to generate C credits, and how will leakage and risk of reversals affect overall estimates of C benefit?

90. Lenihan, J.M.; Bachelet, D.; Neilson, R.P.; Drapek, R. 2008. **Simulated response of conterminous United States ecosystems to climate change at different levels of fire suppression, CO_2 emission rate, and growth response to CO_2.** Global and Planetary Change. 64: 16-25.

This paper reports on a continental analysis of ecosystem response to simulated scenarios of various emission rates, CO_2 fertilization effects, and levels of fire suppression. There are a variety of responses depending on potential inputs (including a variety of regional carbon gains and losses). Climate change effects remain uncertain and impacts and consequences depend on both ecosystem response and fire management.

91. Liski, J.; Pussinen, A.; Pingoud, K.; Mäkipää, R.; Karjalainen, T. 2001. **Which rotation length is favourable to carbon sequestration?** Canadian Journal of Forest Research. 31: 2004-2013.

Rotation length can significantly affect aboveground, soil, and wood product C pools. This study combines four models to determine the effects of simulated rotation length (60, 90, and 120 years over a 300-year horizon) on these three pools for *Picea abies* and *Pinus sylvestris* in a southern Finnish forest, while taking into account fossil C emissions and energy use in harvesting and product manufacturing. Results from the study indicate that for *Pinus sylvestris*, total sequestration is maximized (~ +2.5 percent) and emissions minimized by switching from a 90 (default) to 120-yr rotation length, but the tradeoff is a 10 percent decline in net revenues to landowners. The results for *Picea abies* were less straightforward: whereas the shortest rotation (60 years) maximized the total carbon stock (in part because of significant increases in soil C), it also resulted in the greatest harvest and manufacturing-related emissions, which quickly negates ecosystem C stock surpluses. Increasing the rotation length to 120 years results in slightly lower total C stocks (~ -1 percent), but substantially reduces harvest and manufacturing-related emissions. As a result, the latter strategy is recommended.

92. Luxmoore, R.J.; Hargrove, W.W.; Lynn Tharp, M.; Mac Post, W.; Berry, M.W.; Minser, K.S.; Cropper, W.P.; Johnson, D.W.; Zeide, B.; Amateis, R.L.; Burkhart, H.E.; Baldwin, V.C.; Peterson, K.D. 2002. **Addressing multi-use issues in sustainable forest management with signal-transfer modeling.** Forest Ecology and Management. 165: 295-304.

This publication describes a signal-transfer modeling approach developed for forests in the southeastern United States that provides a “means for gaining insight into possible large scale responses to impacts that have or can only be quantitatively investigated at a small scale.” This modeling approach can help land managers better determine management practices that will meet predefined sustainability goals related to water supply, C sequestration, timber production, and/or biodiversity.

93. Luxmoore, R.J.; Tharp, M.L.; Post, W.M. 2008. **Simulated biomass and soil carbon of loblolly pine and cottonwood plantations across a thermal gradient in southeastern United States.** Forest Ecology and Management. 254: 291-299.

A stand growth and soil C and N model (LINKAGES modified to include RothC) are combined to simulate the effects of N fertilization and increased growing-degree-days on a 25-year *Pinus taeda* stand and for three consecutive 7-year rotations of *Populus* for 17 sites in the southeastern United States. Results for both tree species showed marked increases in aboveground biomass, but C gains were not quantified. Soil C stocks for both tree types were not affected by an increase in growing-degree-days. The authors suggest that "global warming may not initially affect soil C", adding that more data are needed. The response of *Populus* to N fertilization was small but considered significant: 12.9 Mg C/ha to 13.7 Mg C/ha (equal to 0.04 Mg C/ha/yr over 21 years). *Populus* also showed significant declines in relative response to N fertilization with increasing growing-degree-days, indicating that response generally is greater in cooler areas.

94. Magnani, F.; Consiglio, L.; Erhard, M.; Nolè, A.; Ripullone, F.; Borghetti, M. 2004. **Growth patterns and carbon balance of *Pinus radiate* and *Pseudotsuga menziesii* plantations under climate change scenarios in Italy.** Forest Ecology and Management. 202: 93-105.

The study validates a process-based growth model (HYDRALL) and simulates the effects of current and HadCM2 climate conditions on growth in three *Pinus radiate* and one *Pseudotsuga menziesii* plantation in Italy. The climate change scenario increases forest growth, mean annual increment, and water-use efficiency for all stands, and increases net ecosystem exchange only for the *P. menziesii* stand. C sequestration and/or storage is not reported.

95. Masera, O.R.; Cerón, A.D.; Ordóñez, A. 2001. **Forestry mitigation options for Mexico: Finding synergies between national sustainable development priorities and global concerns.** Mitigation and Adaptation Strategies for Global Change. 6: 291-312.

Approximately 116 Mha of Mexico is covered by native forests; about 25.5 Mha is temperate forest land, 66 Mha is semi-arid, and the remainder is tropical. This study simulates countrywide future emissions and forest-based sequestration using multiple model scenarios. The estimated "total mitigation potential" in 2030 is 1,382 x10^6 Mg C in 2030, or about 46 x 10^6 Mg C/yr for the period 2000-2030. This assumes that forest restoration, conservation, and improved management programs continue, and that deforestation rates reach 25 percent of year-2000 level by 2030. This study also estimates potential costs of mitigation efforts.

96. Masera, O.R.; Garza-Caligaris, J.F.; Kanninen, M.; Karjalainen, T.; Liski, J.; Nabuurs, G.J.; Pussinen, A.; de Jong, B.H.J.; Mohren, G.M.J. 2003. **Modeling carbon sequestration in afforestation, agroforestry and forest management projects: the CO_2FIX V.2 approach.** Ecological Modelling. 164: 177-199.

This study describes and presents testing and validation results for version 2 of the CO_2FIX ecosystem-level model (CO_2FIX V.2), which is designed to estimate C balances of alternative management strategies for uneven- or even-aged forests in both temperate and tropical systems. The model estimates C stored in aboveground biomass, soils, and wood products. Testing and validation were conducted on an even-aged *Picea abies* monoculture in central Europe, an even-aged, mixed *Fagus sylvatica* and *Pseudotsuga menziesii* stand in Atlantic Europe, a mixed *Pinus–Quercus* stand in central/southern Mexico, and a mixed cohort agroforestry plantation in Costa Rica. The ability to model multiple cohort stands and simulate both age- and biomass-based tree growth demonstrates the model's flexibility.

97. McCarney, G.R.; Armstrong, G.W.; Adamowicz, W.L. 2008. **Joint production of timber, carbon, and wildlife habitat in the Canadian boreal plains.** Canadian Journal of Forest Research. 38: 1478-1492.

An expansion of a previous effort is presented to model the tradeoffs associated with the joint production of timber supply and wildlife habitat. The previously developed standard linear programming model was expanded to include the Carbon Budget Model of the Canadian Forest Sector (CBM-CFS3). The result is a tool that allows for "extensive marginal cost analysis" of tradeoffs among production of C, timber, and wildlife habitat, and takes into account C in separate biomass and dead organic matter pools for individual forest-cover types.

98. McKenney, D.W.; Yemshanov, D.; Fox, G.; Ramlal, E. 2004. **Cost estimates for carbon sequestration from fast growing poplar plantations in Canada.** Forest Policy and Economics. 6: 345-358.

This study presents a model that estimates storage potential and break even points for afforestation of marginal agricultural land in Canada based on prices for C sequestration and wood products and on agricultural-related opportunity costs. A variety of scenarios demonstrate that afforestation is more economically attractive in western Canada, partially due to higher growth and productivity rates in this region.

99. Neilson, E.T.; MacLean, D.A.; Meng, F.R.; Arp, P.A. 2007. **Spatial distribution of carbon in natural and managed stands in an industrial forest in New Brunswick, Canada.** Forest Ecology and Management. 253: 148-160.

The Carbon Budget Model of the Canadian Forest Sector (CBM-CFS3) is used to simulate C accumulation in living biomass and dead organic material based on timber volume in major stand types in managed vs. unmanaged, as well as hardwood vs. softwood stands in northern New Brunswick, Canada. Species include *Picea mariana, Picea rubens, Picea glauca, Abies balsamea, Pinus banksiana, Fagus grandifolia*, *Betula alleghaniensis*, *Acer saccharum, Populus tremuloides* and *Betula papyrifera.* This paper contains extensive data on estimated mean total C density (Mg/ha) based on stand type, ecoregion, and age class for hundreds of stands. Total ecosystem C, *excluding soil*, is estimated to be 35 Mt over 428,000 ha, or approximately 82 Mg C/ha. General findings include: hardwoods (over 40 years) contain more C than similarly aged softwoods, by virtue of their greater wood density; total C in all biomass pools increased as a function of age, but total C accumulation varied according to species type; at 100 years, planted softwoods contained 94-135 Mg C/ha vs. 92-117 Mg C/ha for natural softwoods and 127-138 Mg C/ha for naturally regenerated hardwoods; C in most stands began to decline after 100 years, but much of this decline in older stands was related to an assumed stand break-up. Although simulation of C stocks was specific to a particular landscape, this modeling method (using merchantable volume to estimate C stock) can be applied more broadly allowing forest managers to optimize for timber values/harvesting relative to C sequestration.

100. Newell, R.G.; Stavins, R.N. 2000. **Climate change and forest sinks: factors affecting the costs of carbon sequestration.** Journal of Environmental Economics and Management. 40: 211-235.

This study examines the cost sensitivity of terrestrial C sequestration to relative prices, opportunity costs, and discount rates. Results show that the marginal cost of avoided deforestation (especially in the tropics) is significantly lower than the cost of afforestation/reforestation and that discount rates are important in overall sequestration quantities. As discount rates increase, the marginal cost of sequestration increases monotonically and forestation also increases, but the present value of C sequestration per acre decreases.

101. Niu, X.; Duiker, S.W. 2006. **Carbon sequestration potential by afforestation of marginal agricultural land in the Midwestern U.S**. Forest Ecology and Management. 223: 415-427.

This study estimates sequestration potential through afforestation of Midwest marginal agricultural land (Magland) based on forest type (coniferous vs. deciduous) and a simplified management tradeoff (short-rotation vs. permanent forest). The study projects changes in aboveground biomass, root, forest floor, and soil organic C pools, and modified sequestration rates based on management impacts

and regional climate conditions such as temperature, precipitation, and site quality. Sequestration potential through Magland afforestation ranges from 508-540 Tg C over 20 years, and from 1018-1080 Tg C over 50 years. These ranges correspond to an estimated total of about 6.5 Mha Magland available in the United States. Coniferous forests show slightly greater overall potential in all scenarios, due to greater forest floor C accumulation (needles take longer to decompose than leaves). Overall mitigative potential would be approximately equal for both scenarios if "best C management" were used in the short rotation scenario, that is, harvested wood should be used for fossil offsets or as long-lived wood products. Otherwise, permanent forest would be slightly better for overall sequestration. Should afforestation occur in these regions, slightly better C outcomes might result from regionally specific decisions with regard to species selected for planting. Magland afforestation could offset roughly 7-8 percent of the region's current GHG emissions over 20 years, or 6 percent over 50 years.

102. Palosuo, T.; Peltoniemi, M.; Mikhailov, A.; Komarov, A.; Faubert, P.; Thürig, E.; Lindner, M. 2008. **Projecting effects of intensified biomass extraction with alternative modeling approaches.** Forest Ecology and Management. 255: 1423-1433.

The study uses two models (MOTTI-YASSO and EFIMOD-ROMUL) to simulate the effects of biomass extraction on forest C balances in six stands (three dominated by *Pinus sylvestris* and three by *Picea abies*) in Finnish forests. There were substantial differences in predictions based upon the model used. Each had different assumptions regarding the timing and intensity of thinnings and the rotation length/timing of final harvest. Model outputs for soil C stocks and forest C stocks were similar for four of six stands, but harvest residue decomposition differed significantly between models. Model comparison does not allow validation but it does allow an exploration of the behavior and theoretical limitations of the models and of the uncertainties associated with model structure.

103. Perez-Garcia, J.; Lippke, B.; Comnick, J.; Manriquez, C. 2005. **An assessment of carbon pools, storage, and wood products market substitution using life-cycle analysis results.** Wood and Fiber Science. 37: 140-148.

Results of a life cycle assessment of ho using production are used to create an accounting tool that "track[s] carbon from sequestration to substitution in forest product end-use markets." Because substitution of wood for more fossil intensive products can have a significant impact on reducing construction and housing-related emissions, management of forests for these products could contribute significantly to mitigation.

104. Pohjola, J.; Valsta, L. 2007. **Carbon credits and management of Scots pine and Norway spruce stands in Finland.** Forest Policy and Economics. 9: 789-798.

This study models a financially optimum stand-level forest management scenario for *Pinus sylvestris*/*Picea abies* stands in Finland, incorporating both timber and C values. Valuing C sequestration leads to higher stocking densities and longer rotation lengths. This finding is similar to those of other studies that compare traditional timber management scenarios with C-inclusive optimization models.

105. Pussinen, A.; Karjalainen, T.; Mäkipää, R.; Valsta, L.; Kellomäki, S. 2002. **Forest carbon sequestration and harvests in Scots pine stand under different climate and nitrogen deposition scenarios.** Forest Ecology and Management. 158: 103-115.

A forest succession applied gap-type model is used to simulate the effects of increased temperature, N deposition, and increased rotation length on timber and C sequestration in a simulated *Pinus sylvestris* stand in southern Finland. Mean ecosystem C stock increased from 60 to 85 Mg C/ha when the rotation length was increased from 40 to 110 years. The rate of increase of C stock declined as rotation length increased (lengthening rotation from 40 to 45 years increased C stock by 3 Mg C/ha, while lengthening rotation from 90 to 95 years increased stock by 1 Mg C/ha) and changed climate conditions led to lower forest C stock due to decreased SOM. Other models suggest CO_2 fertilization leads to greater ecosystem C accumulation.

106. Rokityanskiy, D.; Benítez, P.C.; Kraxner, F.; McCallum, I.; Obersteiner, M.; Rametsteiner, E.; Yamagata, Y. 2007. **Geographically explicit global modeling of land-use change, carbon sequestration, and biomass supply.** Technological Forecasting and Social Change. 74: 1057-1082.

This study reports on the results of a spatially explicit model, "Dynamic Integrated Model of Forestry and Alternative Land Use", or DIMA, to quantify the economic potential for mitigation at both a domestic and international level for decisions on land-use management and biomass. DIMA integrates scenario planning by accounting for dynamic C and energy prices, global biomass supply curves, and global projections of land-use change, C, and bioenergy supply as it relates to socio-economic decision making and opportunity costs for alternative land uses. The model results are compared to those of similar studies. The costs of mitigation using DIMA are similar to other estimates at lower sequestration levels, but DIMA predicts lower-than-average costs at higher quantities (about $150/ton at the 6-7 Tg level, whereas Stavins (1999) predicts exponentially higher costs beyond 4-5 Tg). Results of this study found that C price incentives can generate significant biodiversity and rural development cobenefits, and that C prices factor considerably into avoided deforestation efforts; 5-75 percent of global deforestation can be halted depending on C price. This study notes that the model should be expanded to account for risks and uncertainty (e.g., from fire and pests).

107. Schmid, S.; Thürig, E.; Kaufmann, E.; Lischke, H.; Bugmann, H. 2006. **Effect of forest management on future carbon pools and fluxes: A model comparison.** Forest Ecology and Management. 237: 65-82.

The study compares empirical, semi-empirical, and process-based models to determine effects of four management scenarios (current harvest level, intensified harvest, reduced harvest, and maximum sustainable growth harvest) on C pools and fluxes in four even-aged forest types in Switzerland (coniferous, plateau; mixed deciduous, plateau; beech and fir, pre-Alps; coniferous, Alps). The models predicted similar fluxes, but there were some substantial differences in modeled C pools due in part to different model assumptions and highly heterogeneous climate conditions. Results also show substantial potential for increased C storage, which emphasizes the need for full product accounting for accurate C accounting. Minimally harvested forests maximized C on-site but storage capacity was limited and peaked at 100 years, after which the forests can become a C source. The "maximum sustainable growth/max carbon flow harvest" results in less on-site storage but has can continue mitigating beyond 100 years. The study concludes that no single strategy is "best" due to site-specific conditions.

108. Scott, N.A.; Rodrigues, C.A.; Hughes, H.; Lee, J.T.; Davidson, E.A.; Dail, D.B.; Malerba, P.; Hollinger, D.Y. 2004. **Changes in carbon storage and net carbon exchange one year after an initial shelterwood harvest at Howland Forest, ME.** Environmental Management. 33: S9-S22.

The study examines the changes in C storage and flux 1 year after a shelterwood harvest on a red spruce and eastern hemlock-dominated forest in Maine. Preharvest C levels were 85 Mg C/ha; harvesting removed an estimated 14.9 Mg C/ha in timber, leaving 5.3 and 5.2 Mg C/ha in aboveground slash and root/stump detritus, respectively. About half of the harvested wood was used for long-lived products (estimated half-life of 45 years) and the other half for short-lived paper products (estimated half-life of 3.5 years). Modeling estimated that the site is a net source of C until at least 5 years after harvest, indicating that shelterwood cuts remain a source for at least several years. Additional study and measurement of all C pools over longer time scales is required to determine when the site reverses to sink status and whether this type of management is optimal for this site.

109. Seely, B.; Nelson, J.; Wells, R.; Peter, B.; Meitner, M.; Anderson, A.; Harshaw, H.; Sheppard, S.; Bunnell, F.L.; Kimmins, H.; Harrison, D. 2004. **The application of a hierarchical, decision-support system to evaluate multi-objective forest management strategies: a case study in**

northeastern British Columbia, Canada. Forest Ecology and Management. 199: 283-305.

This study develops a framework for linking multiple forest management models within a hierarchy that facilitates data transfer, and uses it for multiple-use decision-making for a forest in British Columbia, Canada. The integrated decision-support system (DSS) allows tracking of soil, biomass, and dead organic pools under a natural disturbance baseline (control) and two alternative management approaches with higher harvesting levels. Carbon storage is relatively lower in higher harvesting scenarios, but storage declines in the baseline scenario, likely from C releases from fire. Natural and climate-related disturbances should be integrated into DSS systems, which serve "at least four broad purposes: aiding research, guiding management, conveying knowledge, and facilitating a public evaluation of management tradeoffs."

110. 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.

A silvicultural/forest management decision model, FORECAST, calibrated for a mixed wood forest (*Picea glauca, Populus tremuloides*, and *Pinus contorta*) is applied in British Columbia, Canada, to determine the C consequences of 11 management scenarios combining different tree species, harvesting methods and rotation lengths, and fertilization over a 300-year period. Soil C stocks remain relatively stable regardless of treatment, aboveground biomass generally increases with rotation length, and wood product pool C "tended to decline at longer rotations." Only the 150-year pine and 200-year spruce rotations generate C storage that exceeded the natural disturbance scenario, though it is unclear whether the small additional gains were statistically significant. The study notes declines in productivity over multiple rotations, but N fertilization counteracts this by increasing biomass accumulation by as much as 32 percent. Different species are best suited to different rotation lengths: aspen accumulates biomass quickly (1.6-1.8 Mg C/ha/yr) and is ideal for short-rotation (<75 years); pine (1.3-1.7 Mg C/ha/yr) for mid-rotation (75-150 years); and spruce (1.0-1.4 Mg C/ha/yr) for longer rotations (150+ years). The results highlight the tradeoff between on-site ecosystem C storage and timber harvest, and as well as the importance of full product accounting for determining optimal rotation strategies. This study suggests managing stands for a variety of species and rotation lengths to provide for both timber and C sequestration values, or, alternatively, across a landscape to meet multiple criteria. Model outputs can help guide managers toward tree species and rotation lengths that are variably favorable for sequestration or timber.

111. Seidl, R.; Rammer, W.; Jäger, D.; Currie, W.S.; Lexer, M.J. 2007. **Assessing trade-offs between carbon sequestration and timber production within a framework of multi-purpose forestry in Austria.** Forest Ecology and Management. 248: 64-79.

This study uses a hybrid model to determine the effects of three management strategies (age class forestry, 90-year rotations; continuous cover forestry through structural thinnings, 90-year rotations; and moderate conversion to mixed broadleaf, 80-year rotations) on a *Picea abies* forest in Austria, taking into account wood product and bioenergy offset pools. Although the results demonstrate highest overall storage in the unmanaged (control) scenario (134.9 Mg/ha vs. 100.2 Mg/ha for control and continuous cover management, respectively, over 100 years), results do not incorporate the uncertainty and risks associated with alternative strategies. For example, reductions generated through fossil fuel substitution are permanent and real, whereas standing C on the landscape (unmanaged/control) is always subject to unforeseen disturbance-related reversals in C storage. This study also notes that forest-based C sequestration is cost-efficient, but has limited biological and societal potential.

112. Seidl, R.; Rammer, W.; Jäger, D.; Lexer, M.J. 2008. **Impact of bark beetle *(Ips typographus* L.) disturbance on timber production and carbon sequestration in different management strategies under climate change.** Forest Ecology and Management. 256: 209-220.

This study models the combined impact of bark beetle disturbance and climate changes on timber production and C sequestration in secondary *Picea abies* stands in Austria that already were outside their natural range and thus even more vulnerable to threats. Four management alternatives/strategies (age class forestry, continuous cover forestry, conversion to mixed species stands, and no management) for *Picea abies* stands were paired with one baseline and two climate change scenarios (ECHAM4-OPYC3 and HadCM2), and two disturbance scenarios (no disturbance and bark beetle damage). Beetle damage is far more severe (increases of 219 percent in timber losses) for the changed climate vs. baseline scenario. Paired climate change and disturbance scenarios resulted in significantly reduced C storage in managed stands (up to 41 Mg/ha) whereas some unmanaged stand simulations showed slight increases due to stand density effects. When climate change and beetle disturbances are included, continuous cover forestry achieves higher ecosystem C gains than other active management strategies. When bark beetle disturbance is eliminated, all managed stand variants fared better in terms of timber stocks than unmanaged stands in climate change scenarios.

113. Sivrikaya, F.; Keleş, S.; Çakir, G. 2007. **Spatial distribution and temporal change of carbon storage in timber biomass of two different forest management units.** Environmental Monitoring and Assessment. 132: 429-438.

Spatially explicit estimates and mapping of C storage can help link aboveground and belowground processes and help land managers make more informed decisions; this paper proposes a methodology to create spatially explicit carbon estimates. The study maps C storage for two different forest ecosystems, and evaluates the results in the context of changes in land use, forest cover, and species-specific growing stocks.

114. Spring, D.; Kennedy, J.; Mac Nally, R. 2005. **Optimal management of a flammable forest providing timber and carbon sequestration benefits: an Australian case study.** The Australian Journal of Agricultural and Resource Economics. 49: 303-320.

Extending rotation length often is considered a pragmatic option for enhancing sequestration. This study uses stochastic dynamic programming to explore and introduce wildfire risk (and associated unintended C releases) into risk analysis, thinning, and harvesting decisions over a range of potential C prices. The effect of treating saw logs as permanent post-harvest sinks is also analyzed. As C exceeds AU $60/ton, the optimal planned harvest age decreases.

115. Sohngen, B.; Brown, S. 2006. **The influence of conversion of forest types on carbon sequestration and other ecosystem services in the South Central United States.** Ecological Economics. 57: 698-708.

More than 12 million acres of agricultural land in the south-central United States have been shifted into forest plantations over the past 40 years. This study examines potential shifts in land-use as a result of increased demand/prices for timber products, land rental rates, and agricultural commodity prices. Modeled results show that future pine plantations likely will be established by converting natural forests, resulting in reduced capacity for C storage by as much 0.9 Tg C/yr in aboveground biomass and harvested wood products in Arkansas, Louisiana, and Mississippi. Natural forests and associated greater C storage might be maintained through subsidies.

116. Stinson, G.; Freedman, B. 2001. **Potential for carbon sequestration in Canadian forests and agroecosystems.** Mitigation and Adaptation Strategies for Global Change. 6: 1-23.

Canadian forests currently are a net source of emissions. A large though ultimately limited land area and the risk of catastrophic C losses from disturbances limit the amount of C that can be stored in Canada's forest ecosystems, but long-term opportunities for mitigation exist through fossil fuel displacement. This study examines the potential for optimizing mitigation in Canadian agroecosystems and in four forest ecosystems: boreal aspen, boreal white spruce, coastal Douglas fir, and Acadian mixed tolerant hardwoods through four management strategies: maximum sustained yield (MSY) management for pulp logs, MSY management for saw logs, MSY management for biofuel, and creation of protected forest C reserves. The C storage potential of each of the four strategies for each ecosystem is discussed. In all ecosystem types, total mitigation is greatest after 200 years with the protected C reserve strategy (131 Mg C/ha for boreal aspen, 161 Mg C/ha for boreal white spruce, 473 Mg C/ha for coastal Douglas fir, and 94.7 Mg C/ha for Acadian mixed hardwoods). However, mitigation strategies that entail displacement of more energy-intensive products are irreversible and thus more certain (not subject to catastrophic loses of C from the landscape). This untitled "simple budget model" (which takes into account aboveground and belowground C, harvested wood products, and displaced emissions) assumes suppression of "natural" disturbances, which typically occur on 30-200 year intervals. In reality, however, suppressing natural disturbances could be costly, risky, and/or counterproductive (e.g., fire suppression could lead to more catastrophic fires). As a result, it is worth considering the benefits of other management options, particularly MSY management for saw logs, which resulted in C storage that was nearly as substantial.

117. Thürig, E.; Palosuo, T.; Bucher, J.; Kaufmann, E. 2005. **The impact of windthrow on carbon sequestration in Switzerland: a model-based assessment. Forest Ecology and Management.** 210: 337-350.

Although most forests act as important C sinks, disturbances such as windstorms can result in premature and potentially large C releases, especially in older forests. This study examines the effects of wind disturbance on Swiss forests, typically dominated by *Picea abies, Fagus*, and *Abies alba*, using two validated models: a forest management and a C model. This study combines two management scenarios (business as usual [BAU] and reducing large logs [RLL]), two storm scenarios, and two post-storm prescriptions for a total of 10 management-disturbance scenarios and finds that: BAU management scenarios result in substantial accumulations of C on the landscape, whereas RLL management led to a negative total C budget after 30 years. Forest soil C increases are slight and slow; and that post-disturbance clearing only slightly reduces the C budget. A 30 percent increase in the frequency of storms had "only a small impact on carbon sequestration in forests" in part because the input of windthrown timber to soil C can more than offset the C released from uprooting. A "best" mitigation strategy cannot be recommended without accounting for long-term soil C effects and the use of salvaged wood.

118. Trofymow, J.A.; Stinson, G.; Kurz, W.A. 2008. **Derivation of a spatially explicit 86-year retrospective carbon budget for a landscape undergoing conversion from old-growth to managed forests on Vancouver Island, BC.** Forest Ecology and Management. 256: 1677-1691.

The study employs the CBM-CFS3 model along with historical disturbance maps, ortho-photographs, and a 1919 timber cruise map to reconstruct the C budget for the *Pseudotsuga menziesii*-dominated Oyster River area in eastern Vancouver Island in British Columbia, Canada, to determine C-related effects of conversion from an old-growth to managed forest. It was difficult to construct a C budget due to the difficulty of reconstructing the initial condition of the forest. The study estimates total aboveground, belowground, soil and total C storage of 271, 55, 237, and 749 Mg C/ha in 1920 (prior to logging) which is similar to modern-day total ecosystem storage in H.J. Andrews Experimental Forest in Oregon (625 Mg C/ha) and Olympic National Park in Washington (819 Mg C/ha). Not surprisingly, C stocks declined from 1930-1945 when the forest was subjected to fires and logging. The forest remained a C source until 1954, losing an average of 365-411 Mg/ha for a total of 0.91-1.02 Mt C. Harvesting of second growth in the 1980s again reduced the C budget but stocks recovered to 504-533 Mg C/ha by 1998. "Despite their high productivity, the area's forests are not likely to obtain C densities of the landscape prior to industrial logging because the stands will not reach pre-logging ages."

119. Van Wijk, M.T.; Dekker, S.C.; Bouten, W.; Kohsiek, W.; Mohren, G.M.J. 2001. **Simulation of carbon and water budgets of a Douglas-fir forest.** Forest Ecology and Management. 145: 229-241.

A forest growth-hydrology model (FORGRO-SWIF) that measures water-use efficiency was validated and used to model forest water use for thinned and unthinned stands in a *Pseduotsuga menziesii* forest in the Netherlands. This study finds the C changes in the unthinned stand are double the C sink of the thinned stand (10-12.1 Mg C/ha/yr vs. 4.3 -6.2 Mg C/ha/yr). Water-use efficiency is higher in the unthinned scenario.

120. Vetter, M.; Wirth, C.; Bottcher, H.; Churkina, G.; Schulze, E.D.; Wutzler, T.; Weber, G. 2005. **Partitioning direct and indirect human-induced effects on carbon sequestration of managed coniferous forests forests using model simulations and forest inventories.** Global Change Biology. 11: 810-827.

This study attempted to isolate the effects of indirect human-driven changes (N deposition and CO_2 fertilization) and forest age class distribution and legacy on the total C sink of a *Picea abies/Pinus sylvestris*-dominated coniferous forest in Germany. The study uses the BIOME-BGC model to simulate C, N, water fluxes, forest age dynamics, and site history and finds that: mature forests (>70 years) are significant C sinks of up to 5 Mg C/ha/yr; mature and young stands both show significant responses to N deposition, whereas middle-aged stands were already growing at their maximum rate and did not exhibit much additional response; and CO_2 fertilization acts to improve water-use efficiency and drives greater biomass gains, especially at low and medium elevation sites. Indirect human influences result in a 33 percent increase in forest productivity and the age-class distribution resulting from previous management decisions accounts for roughly 8-17 percent of the current sink. Findings differ significantly from Caspersen et al. (2000), who concluded that indirect human impacts play a much smaller role (2 percent) in increasing forest productivity based on repeated forest inventory data.

III. Experiments with Some Pools Modeled

121. Bauer, G.A.; Bazzaz, F.A.; Minocha, R.; Long, S.; Magill, A.; Aber, J.; Berntson, G.M. 2004. **Effects of chronic N additions on tissue chemistry, photosynthetic capacity, and carbon sequestration potential of a red pine *(Pinus resinosa* Ait.) stand in the NE United States**. Forest Ecology and Management. 196: 173-186.

Results from a 15-year study of N amendments on *Pinus resinosa* on the Harvard forest in Massachusetts demonstrate that while N amendments have significantly increased foliar N content, the treatment reduced foliar longevity and decoupled the photosynthesis-N relationship resulting in decreased photosynthetic capacity (of fertilized trees) by 50 percent. An increase in N foliar content does not correspond to a greater capacity for C assimilation primarily because increased N reduces foliar longevity. Authors used the PnET-Day model to determine effects on long-term C balance; simulation results are vague and general, suggesting a reduced net C gain.

122. Banfield, G.E.; Bhatti, J.S.; Jiang, H.; Apps, M.J. 2002. **Variability in regional boreal forest ecosystems: results from West-Central Alberta.** Forest Ecology and Management. 169: 15-27.

This study uses a combination of forest inventory data, model simulations, field-observed plot data, and soil-polygon information to model regional estimates and spatial variation in aboveground biomass, forest floor, and soil C stocks for a transitional boreal region in Alberta, Canada that is dominated by *Pinus contorta* with *Populus tremuloides* and *Picea glauca*. The current regional average aboveground biomass C was estimated at 43 Mg C/ha. The model revealed the major role of natural and human disturbance from 1920-1995. Improved forest C budget models can better help track management and climate-induced changes.

123. Hoover, C.; Stout, S. 2007. **The carbon consequences of thinning techniques: Stand structure makes a difference**. Journal of Forestry. 105: 266-270.

Thinning often is used to increase the quality and size of merchantable timber. This study examines stands that have been thinned twice over 25 years using three techniques (thinned from below, 60-70 percent target density; thinned from middle, 60-70 percent target density; and thinned from above). The study finds a net C benefit of 0.15 Mg C/ha/yr (in terms of live aboveground biomass, slash, deadwood, and products) in stands that were thinned from below compared to the control. Stands thinned from middle or above exhibit net C losses of 0.99 Mg C/ha/yr and 1.41 Mg C/ha/yr, respectively, as compared to the control.

124. Kashian, D.M.; Romme, W.H.; Tinker, D.B.;Turner, M.G.; Ryan, M.G. 2006. **Carbon storage on landscapes with stand-replacing fires.** BioScience. 56: 598-606.

The effects of stand-replacing fires on short and longer-term landscape C storage are examined for coniferous forests in light of fire disturbance becoming more frequent and more likely due to historical and climate-related factors. Near-term effects of wildfire on forest ecosystem C balance were considered, including the balance between C loss in deadwood decomposition and C gain in new vegetation. Longer-term C storage trajectories for a landscape are related to regeneration profiles. Changing fire frequency affects stand age structure and increasing frequency changes the age distribution of forest stands, but equilibrium values of landscape C storage are resistant to change unless fire intervals become substantially shorter. The 1988 Yellowstone wildfires were used to explore near and longer-term C dynamics. Results showed direct fire-related C losses of 13.6 Mg C/ha; 15.3 Mg C/ha will be lost through decomposition over 250 years following the 1988 fire; that the landscape will return to prefire NEP levels by 2028; and that total C lost will be recovered in 230 years.

125. Martin, J.M.; S.T.G., Plaut, J.; Holmes, B. 2005. **Carbon pools in a boreal mixedwood logging chronosequence.** Global Change Biology. 11: 1883-1894.

This study examines aboveground carbon and detritus in a mixedwood boreal forest (dominated by *Betula papyrifera*, *Larix laricina*, *Picea mariana*, *Picea glauca*, *Pinus banksiana*, *Populus balsamifera, Populus tremuloides*) in Manitoba, Canada. The effects of harvesting on C in these forests had not been studied previously, although previous studies used the BOREAS model, which was designed for relatively pure boreal forest types. Four even-aged mixed-wood stands that were 11, 18, 30, and 65 years old are considered, the first three of which originated following a clearcut and the fourth originated following wildfire. C density in these mixedwood stands is 47 percent higher than a pure wet *Picea mariana* stand, and 44 percent higher than a pure *Pinus banksiana* stand (all boreal). Possible explanations include: litterfall, forest floor, and tree N content are greater for deciduous vs. coniferous forests; natural succession in a boreal forest ecosystem includes a transition from deciduous to coniferous trees, and canopy production efficiency and transpiration declines during this succession; and/or that mixed-wood stands have multilayered canopies that can support greater foliage mass.

126. McNulty, S.G. 2002. **Hurricane impacts on U.S. forest carbon sequestration.** Environmental Pollution. 116: S17-S24.

Hurricanes can be a major disturbance factor on forests. Ultimate impacts on the United States C budget depend on how much dead biomass results from a typical storm, the fate of the dead biomass (whether it is allowed to decay, used for bioenergy or wood products) and whether hurricanes confer long-term benefits on forests, e.g., increased nutrient inputs that may result in increased productivity. The increase in the detritus pool from four major hurricanes during the 20th century ranged from 2.9 to 20 Tg C. Results indicate that a single hurricane can "convert the equivalent of 10 percent of the total annual U.S. forest carbon sequestration from living to dead wood." Although some downed wood is harvested after storms, much remains inaccessible. Hurricane damage can increase wildfire risk and longer-term C losses associated with leaf area recovery time and reduced stem stocking probably are not offset by short-term increases in forest. In hurricane-prone areas of the southeast, managers can mitigate against future storm damage by planting more longleaf pine and hardwoods, both of which are more storm resistant than other pines.

127. Radtke, P.J.; Amateis, R.L.; Prisley, S.P.; Copenheaver, C.A.; Chojnacky, D.C.; Pittman, J.R.; Burkhart, H.E. 2009. **Modeling production**

and decay of coarse woody debris in loblolly pine plantations.** Forest Ecology and Management. 257: 790-799.

The volume, density, and mass of CWD at 36 *Pinus taeda* plots throughout the southeastern United States were sampled. The plots were installed in 21-year-old stands that remained from 186 stands established in 1980-82 to study thinning effects. Data on tree mortality data from the original study were used to create decay classes for dead trees. These were paired with on-site CWD data to create prediction equations for CWD production, decay, and yield. The equations can predict CWD yield at the tree to plantation level, and can estimate CWD C stocks for loblolly pine plantations throughout the southeast.

128. Ryan, M.G.; Binkley, D.; Fownes, J.H.; Giardina, C.P.; Senock, R.S. 2004. **An experimental test of the causes of forest growth decline with stand age.** Ecological Monographs. 74: 393-414.

This study seeks to determine the reason for a decline in aboveground wood production (and thus C production) after canopy closure in stands of *Eucalyptus saligna* in Hawaii. Aboveground and belowground C budgets were measured for 6 months to 6.5 years after planting. Two stocking density levels (10,000 and 1,111 trees/ha) and three fertilization treatments were included. Meteorological and ecophysiological data were used to estimate C storage and flux, foliage and wood respiration rates, foliar nutrients, photosynthetic capacity, and other variables to determine whether the decline in aboveground wood/C production decline was related to a: 1) partitioning shift from wood production to respiration; 2) proportional reduction in GPP driven by nutrient limitation, reduced canopy leaf area/photosynthesis, increased abrasion between tree canopies, or other reasons; or 3) combination of these. Results support the combination hypothesis: GPP declined and the decline in wood/C production was proportionally greater than the decline in canopy photosynthesis.

129. Sampson, D.A.; Waring, R.H.; Maier, C.A.; Gough, C.M.; Ducey, M.J.; Johnsen, K.H. 2006. **Fertilization effects on forest carbon storage and exchange, and net primary production: A new hybrid process model for stand management.** Forest Ecology and Management. 221: 91-109.

A hybrid model was calibrated and validated to predict the effects of N fertilization on *Pinus taeda* stands growing in nutrient poor soils of North Carolina. N fertilization was used to increase leaf-area index and NEP by tenfold over the control treatment (0.73 Mg C/ha/yr over a 12-year period). Seasonal uptake patterns suggested that "autumn and winter may be critical periods for C uptake in nutrient-limited [*Pinus taeda*] stands." However, accumulation of aboveground biomass was 27 percent less than that found by Jokela and Martin (2000) in intensively managed loblolly pine stands in Florida. The C impacts of intensively managed stands depend heavily on management and its long-term effect on soil C and on whether harvested wood is made into short- or long-lived products; neither of these factors was included in this study.

130. Taylor, A.R.; Wang, J.R.; Kurz, W.A. 2008. **Effects of harvesting intensity on carbon stocks in eastern Canadian red spruce *(Picea rubens)* forests: An exploratory analysis using the CBM-CFS3 simulation model.** Forest Ecology and Management. 255: 3632-3641.

This study compares results from a C budget model to actual C stocks and changes in *Picea rubens* dominated stands in Nova Scotia, Canada. Simulations of partial and clearcut harvests over 240 years were run to determine effects on C stocks. Although the partial harvest resulted in more C retained on the landscape than the clearcut (327.3 Mg C/ha vs. 305.8 Mg C/ha), the latter generated more merchantable timber (132.4 Mg C/ha vs. 115.6 Mg C/ha). The partial-cut scenario resulted in more DOM C, likely the result of greater DOM inputs from selective harvesting methods. Additional research is needed to determine harvesting scenarios that would optimize timber output along with landscape C storage.

131. Thornton, P.E.; Law, B.E.; Gholz, H.L.; Clark, K.L.; Falge, E.; Ellsworth, D.S.; Goldstein, A.H.;

Monson, R.K.; Hollinger, D.; Falk, M.; Chen, J.; Sparks, J.P. 2002. **Modeling and measuring the effects of disturbance history and climate on carbon and water budgets in evergreen needleleaf forests.** Agricultural and Forest Meteorology. 113: 185-222.

The effects of disturbance history and climate change on C and water fluxes are reported for seven evergreen coniferous forests in California, North Carolina, Florida, Maine, Oregon, Colorado, and Washington using data and findings from observations of canopy flux with comparisons to modeled effects. The unique disturbance history of each site (ranging from clearcut to selective harvest to low-level and stand-replacing fires) is described. Results indicate that variations between sites are primarily related to disturbance history while other site-specific and changing N deposition and atmospheric CO_2 concentrations play a secondary role. In all cases, predicted peak emissions related to disturbance occur within 2 years of disturbance, after which each site continues as a source of emissions for 4-16 years and then becomes a strong and gradually diminishing sink. The effects of CO_2 fertilization are limited by nutrient availability but effects are greatest following disturbance when nutrient availability is high and plant demand is relatively low.

IV. Literature Reviews and Meta-analyses

132. Birdsey, R.A.; Alig, R.; Adams, D. 2000. **Mitigation activities in the forest sector to reduce emissions and enhance sinks of greenhouse gases.** In: Joyce, L.A.; Birdsey, R.A., eds. The impact of climate change on America's forests: a technical document supporting the 2000 USDA Forest Service RPA assessment. Gen Tech. Rep. RMRS-59. Ft. Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station: 112-131.

This chapter provides a high-level analysis of opportunities to reduce sources (substitute wood products for more energy-intensive products; reduce the energy required to grow, harvest, and process timber; reduce the risk of catastrophic wildfire), enhance sinks (afforest land; avoid deforestation; improve management; reduce harvest/extend rotation; encourage agroforestry), and achieve concurrent source reductions/sink enhancements of GHGs (substitute bioenergy for fossil-based energy; increase C capture and retention in wood products; increase paper and wood reuse/recycling; enhance urban forestry/tree plantings). The estimated increase in U.S. forest C stocks from 1952-1992 was 281 Tg C/yr. The study estimates reduced future rates of storage (2000-2040), on the order of 183 Tg C/yr. A summary table of enhanced C storage opportunities by practice is included. Additional opportunities that span the aforementioned options for reducing sources and/or simultaneously enhancing sinks are estimated at 210 Tg C/yr.

133. Birdsey, R.; Pregitzer, K.; Lucier, A. 2006. **Forest carbon management in the United States: 1600-2100.** Journal of Environmental Quality. 35: 1461-1469.

This study explains how past land-use practices in the United States have and will continue to affect the forest C budget. From 1600-1800, U.S. forests were in C balance with the atmosphere. These forests have been a significant sink in recent decades due to regrowth after the abandonment of agricultural land. The strength of the sink is declining but additional sequestration of 100-200 Tg C/yr may be possible through a combination of afforestation, mineland reclamation, forest restoration and management, agroforestry, and the use of bioenergy and wood products. This will require improved monitoring and technology transfer to land managers.

134. Conant, R.T.; Paustian, K.; Del Grosso, S.J.; Parton, W.J. 2005. **Nitrogen pools and fluxes in grassland soils sequestering carbon.** Nutrient Cycling in Agroecosystems. 71: 239-248.

The study demonstrates that anywhere from 10-125 percent of C sequestration gains due to changes in management practices on grasslands were offset by increases in N_2O flux. Conversely, altering management to minimize N_2O flux may significantly benefit climate change mitigation efforts. Some studies have shown that N sequestration and decreased N mineral availability lead to reduced N_2O flux though this result was not corroborated by this study. Authors have demonstrated that N fertilization, relatively common on forests and grasslands, does not always increase C sequestration. Production, transport, and increased N_2O flux that may be associated with fertilizer application can increase both CO_2 and N_2O emissions.

135. Gielen, B.; Ceulemans, R. 2001. **The likely impact of rising atmospheric CO_2 on natural and managed *Populus*: a literature review.** Environmental Pollution. 115: 335-358.

This publication is a comprehensive review of literature pertaining to CO_2 enrichment studies, including those related to controlled environment and open-top chambers, natural springs, and FACE experiments. There is an obvious response by aboveground and belowground biomass of *Populus* spp. to CO_2 enrichment: responses for total or stem biomass ranged from 22-90 percent increased productivity (mean = 33 percent); leaf area increased by 7-103 percent; and root mass in both potted and field experiments generally increased, though long-term relative growth response to CO_2 fertilization remains unclear and is not necessarily greater than for slower growing species. Forest management (especially plantation management) can be modified (rotation lengths shortened) to take advantage of greater productivity. Wood quality and vulnerability of certain poplar species to fungus, insects, and disease under changed climate conditions must be considered carefully.

136. Gower, S.T. 2003. **Patterns and mechanisms of the forest carbon cycle**. Annual Reviews Energy and Environment. 28: 169-204.

This publication provides an accessible general overview of the forest C cycle and the effects of climate-related disturbances and anthropogenic perturbations on C balances and exchanges of CO_2 with the atmosphere. The forest C cycle is explained in relation to NPP, soil surface CO_2 flux, and NEP. Disturbances related to climate change and their effects on forest ecosystems are summarized; a brief, high-level explanation of C sequestration in forest vegetation, soils, and forest products as well as offsets related to fossil fuel substitution is provided.

137. Han, F.; Plodinec, M.; Su, Y.; Monts, D.; Li, Z. 2007. **Terrestrial carbon pools in southeast and south-central United States.** Climatic Change. 84: 191-202.

This study estimates current annual rates of C sequestration in Alabama, Arkansas, Florida, Georgia, Louisiana, Mississippi, North Carolina, South Carolina, Tennessee, Texas, and Virginia, develops estimates for regional sinks, and determines how much of the region's annual emissions might be offset by terrestrial sequestration. However, the study relied on 1990 regional GHG emission estimates (more recent estimates were not available at the time), and on forest C pool estimates from 1996 and growth rates from 1999. The study estimates that terrestrial sinks capture 23 percent of total regional (southeast/south-central) GHG emissions and that total sink size in this region is 130 Tg C/yr (more than 158,300 ha).

138. Heath, L.S.; Smith, J.E. 2000. **An assessment of uncertainty in forest carbon budget projections.** Environmental Science & Policy. 3: 73-82.

This study analyzes uncertainty forecasts for forest C inventory and flux. For inventory, uncertainty estimates were ±9 percent for 2000, increasing to 11 percent in 2040. The greatest sources of uncertainty are soil and tree C for inventory estimates. Uncertainties related to flux estimates are "higher and more variable" than stock uncertainties, and greatest sources of uncertainty are related to volume growth and volume removals. Different approaches are required to reduce uncertainty in flux estimates compared to those that are required to reduce uncertainty in stock (inventory) estimates.

139. Houghton, R.A. 2003. **Why are estimates of the terrestrial carbon balance so different?** Global Change Biology. 9: 500-509.

Author reviews recent top-down and bottom-up estimates of the global C sink and sorts by source and decade. A northern mid-latitude sink of 2 Pg/yr is estimated primarily as a result of historical land-use change.

140. Houghton, R.A.; Hackler, J.L. 2000. **Changes in terrestrial carbon storage in the United States. 1: The roles of agriculture and forestry.** Global Ecology & Biogeography. 9: 125-144.

This study examines ways in which historical land-use patterns have affected the U.S. C flux, provides estimates of flux magnitude and direction for past years based on these changes, and compares the U.S. C sink with atmospheric modeling of the North American C sink.

141. Houghton, R.A.; Hackler, J.L.; Lawrence, K.T. 2000. **Changes in terrestrial carbon storage in the United States. 2: The role of fire and fire management.** Global Ecology & Biogeography. 9: 145-170.

This is a second in a series of chapters that examines historical change in the U.S. C profile. In examining the role of fire on terrestrial C storage and accumulation, this study estimates the changes in land use (from forest to agricultural land) that reduced fire incidence as well as the effects of fire suppression. The study hypothesizes that this allowed for woody encroachment into some areas. Results show a total U.S. terrestrial sink of 390 Tg C/yr from 1950-1990, a significant portion of which is related to fire exclusion and fire management. This paper contains much data related to historical burn intervals and current and historical terrestrial C accumulation in U.S. regions as a result of fire management.

142. Hu, H.; Wang, G.G. 2008. **Changes in forest biomass carbon storage in the South Carolina Piedmont between 1936 and 2005.** Forest Ecology and Management. 255: 1400-1408.

Researchers examined changes in C stock in South Carolina's Piedmont region. Conversion of 2.8 Mha of land from agricultural use to forest land between 1936 and 2005 resulted in a net C gain of 1.19 Tg C/yr, or about 0.43 Mg C/ha/yr. Eighty percent of these gains were in aboveground biomass. Although soil C usually constitutes at least half of the total forest C pool, its soil content rarely is subject to rapid change.

143. Hyvonen, R.; Agren, G.I.; Linder, S.; Persson, T.; Cotrufo, M.F.; Ekblad, A.; Freeman, M.; Grelle, A.; Janssens, I.A.; Jarvis, P.G. 2007. **The likely impact of elevated CO_2, nitrogen deposition, increased temperature and management on carbon sequestration in temperate and boreal forest ecosystems: a literature review.** New Phytologist. 173: 463-480.

This study summarizes single-factor climate feedback findings and explores the combined effects of increasing CO_2, temperature, and N deposition, and intensified management. The study states that: 1) hundreds of studies have shown that elevated CO_2 concentration stimulates tree growth but that long-term effects remain uncertain, including whether growth will be restricted by nutrient availability; 2) single-factor studies have found that elevated temperature increases photosynthetic rates, CO_2 and temperature frequently interact, and although leaf-scale photosynthetic rates may increase, increases in leaf-area may create more stand shade and counteract productivity increases; 3) decomposition of leaf litter increases with increasing temperature but the effect of temperature/response of leaf litter becomes less clear as the litter reaches later stages of decomposition; 4) soil respiration may briefly increase, but a long-term effect is unlikely; 5) N deposition likely will increase C sequestration in nutrient limited environments; 6) the effects of N deposition on soil remain uncertain but a recent meta-analysis suggests that litter decomposition is stimulated at sites with low ambient N deposition (<5 kg/ha/yr) and high-quality litters, but that sites with moderate N deposition or low-quality litters experience reduced decomposition rates (5-10 kg/ha/yr). The study also includes a table that summarizes the qualitative effects of various management practices and disturbance events on soil, biomass, and ecosystem C stock. Ecosystem C stocks generally increase with low-moderate site preparation, a change in species composition from broadleaves to conifers, fertilization, and increased rotation lengths. Ecosystem C stocks decrease with changes in species composition from conifers to broadleaves, and with some thinning methods. Ecosystem C may increase, decrease, or remain the same with: prescribed burning, peatland drainage, intensive site preparation, and harvesting method used.

144. Jones M.B.; Donnelly, A. 2004. **Carbon sequestration in temperate grassland ecosystems and the influence of management, climate and elevated CO_2.** New Phytologist. 164: 423-439.

This is a thorough overview of the dynamics of C storage in temperate grassland ecosystems (ecosystems in which herbaceous species are the dominant vegetation) including a review of the literature on the effects of management and climate change on grassland C sequestration. The accumulation of C in grasslands is controlled largely by site productivity; estimates of when the soil C pool will reach a saturation point for temperate grasslands range from 10-100 years. Management actions to increase C storage on grasslands include fertilization, irrigation, intersowing of grasses and legumes, and introducing productive forage grasses. It is difficult to determine the long-term effects of elevated concentrations of CO_2 on grasslands: elevated CO_2 concentrations often lead to increases in NPP of grasslands and much uncertainty remains with respect to respiration, turnover, C root allocation, and interaction with other nutrient demands. Sequestration rates for temperate pasture range from 0 to 8 Mg/ha/yr; improved management of U.S. pastureland may increase sequestration by 0.2-0.5 Mg C/ha/yr.

145. Litton, C.M.; Raich, J.W.; Ryan, M.G. 2007. **Carbon allocation in forest ecosystems.** Global Change Biology. 13: 2089-2109.

This meta-analysis reviews of 63 studies to determine the limits, patterns, and plasticity of biomass, flux, and partitioning—three critical components of C allocation. Nine broad generalizations are presented, including: biomass should not be used to infer flux or partitioning, increased GPP increases C flux of all ecosystem components, and C fluxes vary more than partitioning across different forests, but partitioning is critical to understanding allocation and requires additional study.

146. Luyssaert, S.; Schulze, E.-D.; Borner, A.; Knohl, A.; Hessenmoller, D.; Law, B.E.; Ciais, P.; Grace, J. 2008. **Old-growth forests as global carbon sinks.** Nature. 455: 213-215.

This publication challenges the traditional assumption that old-growth forests are C neutral. Data from 519 temperate and boreal forests shows that NEP is positive for most forests that are 15-800 years old. Unmanaged primary forests constitute 30 percent of the global forest area; half of this area is in northern temperate and boreal regions. These primary temperate and boreal forests provide 10 percent of global NEP and sequester 1.3 +/- 0.5 Gt C/yr, but their protection is not assured by current policies Release of C might be significant if these forests are disturbed.

147. Malmsheimer, R.W.; Heffernan, P.; Brink, S.; Crandall, D.; Deneke, F.; Galik, C.; Gee, E.; Helms, J.A.; McClure, N.; Mortimer, M.; Ruddell, S.; Smith, M.; Stewart, J. 2008. **Forest management solutions for mitigating climate change in the United States.** Journal of Forestry. 106: 115-118.

This entire issue of the Journal of Forestry is devoted to mitigation of climate change through forest management, and contains the following chapter headings: Overview of Global Climate Change (1); Potential Effects of Climate Change on Forests (2); Preventing GHG Emissions through Wood Substitution (3); Preventing GHG Emissions through Biomass Substitution (4); Preventing GHG Emissions through Wildfire Behavior Modification (5); Preventing GHG Emissions through Avoided Land- Use Change (6); Reducing Atmospheric GHGs through Sequestration (7); Markets for Forest Carbon Offset Projects (8); and Opportunities and Challenges for Society, Landowners, and Foresters (Conclusion).

148. Magnani, F.; Mencuccini, M.; Borghetti, M.; Berbigier, P.; Berninger, F.; Delzon, S.; Grelle, A.; Hari, P.; Jarvis, P.G.; Kolari, P.; Kowalski, A.S.; Lankreijer, H.; Law, B.E.; Lindroth, A.; Loustau, D.; Manca, G.; Moncrieff, J.B.; Rayment, M.; Tedeschi, V.; Valentini, R.; Grace, J. 2007. **The human footprint in the carbon cycle of temperate and boreal forests.** Nature. 447: 848-850.

This comprehensive meta-analysis of northern hemisphere forests shows that while temporal disturbances and forest management play a critical role in forest C sequestration and variability, increased N deposition due to human activity is a primary driver of NEP in temperate forests. The high correlation (R^2 =0.97) between average C sequestration and wet N deposition is often obscured by age effects when studying individual stands. Wet deposition rates are as high as 9.8 kg N/ha/yr, which equals about 15 kg N/ha/yr total N deposition. Results also show that: saturation is unlikely, ecosystem responses are adverse (including soil acidification, nutrient imbalances, tree damage) only at deposition rates of 50-60 kg N/ha/yr, and ecosystem response is a function of the addition rate rather than the cumulative N input. The C balance of temperate and boreal forests is being controlled and driven by human influence, be it direct (through forest management) or indirect (through N deposition).

149. Markewitz, D. 2006. **Fossil fuel carbon emissions from silviculture: Impacts on net carbon sequestration in forests.** Forest Ecology and Management. 236: 153-161.

This study highlights that few papers have quantified and evaluated fossil emissions related to forest management and silvicultural activities. These must be accounted for in order to create net positive C balances from forest management. The author reviews and synthesizes data ranging from peer-reviewed articles to equipment owner manuals to estimate C emissions related to silvicultural activities. These data are used to parameterize a model for a short-rotation (25 year) southern pine plantation. Total C emissions from silvicultural activities over this period totaled <3 Mg C/ha. These emissions are comparable to the amount of gains in soil C and paper product storage over a 100-year period for this type of stand. This study suggests that extending rotation lengths to grow saw-log quality trees and creating long-lasting wood products would "exceed the incurred C emissions by threefold," that is, these practices would exceed emissions by 35 Mg C/ha over 100 years.

150. Montagnini, F.; Nair, P.K.R. 2004. **Carbon sequestration: An underexploited environmental benefit of agroforestry systems.** Agroforestry Systems. 61: 281-295.

This publication extols the benefits of agroforestry systems, which can provide significant C sequestration benefits, particularly when perennial rather than annual crops are planted. A review of the agroforestry literature is reviewed provides estimates of sequestration potentials in different biomes. The estimated potential for enhanced sequestration through agroforestry in the United States is as high as 90.3 Tg C/yr (aboveground and belowground storage). It includes a somewhat outdated overview of PES schemes in both tropical and temperate regions.

151. Myneni, R.B.; Dong, J.; Tucker, C.J.; Kaufmann, R.K.; Kauppi, P.E.; Liski, J.; Zhou, L.; Alexeyev, V.; Hughes, M.K. 2001. **A large carbon sink in the woody biomass of Northern forests.** Proceedings of the National Academy of Sciences. 98: 14784.

The authors investigate the terrestrial sink potential of northern temperate and boreal forests in the United States, Canada, and Eurasia (Finland, Norway, Sweden, Russia), which cover an estimated 1.4-1.5 billion ha. The study examines high-resolution satellite data (8-km resolution, 64-km^2 pixel area) from radiometers on board NOAA satellites and compares/matches them to ground-up 1980s and 1990s inventory data from the six countries. Spatially explicit maps that highlight carbon pools and changes in C pool were developed. Results indicate C gains exceeding 0.3 Mg C/ha/yr in many parts of the Eurasian boreal and U.S. and Canadian temperate forests, and losses of 0.1 Mg C/ha/yr in some parts of the Canadian boreal forest. The study includes a table that summarizes remote sensing estimates of C pools and sinks broken down by country, including estimates for China and Japan. Average forest C pools are largest in the United States (57.91 Mg/ha); annual sinks are most significant in United States (141.53 Mt C/yr) and Russia (283.59 Mt C/yr). Although results may contain inherent uncertainties and calibration errors, they nonetheless represent an important step toward understanding global C dynamics. This is the first study in which high-resolution satellite estimates of C pool changes are validated with ground data.

152. Nabuurs, G.J.; Masera, O.; Andrasko, K.; Benitez-Ponce, P.; Boer, R.; Dutschke, M.; Elsiddig,

E.; Ford-Robertson, J.; Frumhoff, P.; Karjalainen, T.; Krankina, O.; Kurz, W.A.; Matsumoto, M.; Oyhantcabal, W.; Ravindranath, N.H.; Sanz Sanchez, M.J.; Zhang, X. 2007. **Forestry.** In: Metz, B.; Davidson, O.R.; Bosch, P.R.; Dave, R.; Meyer, L.A., eds. Climate change 2007: mitigation. Contribution of working group III to the fourth assessment report of the Intergovernmental Panel on Climate Change. Cambridge, United Kingdom: Cambridge University Press. 851 p.

This chapter of the IPCC's Working Group III Assessment Report, is a high-level synthesis and overview of the role of forests in the global C balance and flux. This includes an assessment of C stocks in living biomass by geographic regions, mitigation options (maintain/increase forest area; maintain/enhance site-level C density; maintain/enhance landscape level C stocks; and maintain/enhance the use of wood products and bioenergy as substitutes for fossil fuel or fossil fuel intensive products), potential sink capacities vis-à-vis costs, adaptation strategies, and policy barriers and opportunities.

153. Narayan, C.; Fernandes, P.M.; van Brusselen, J.; Schuck, A. 2007. **Potential for CO_2 emissions mitigation in Europe through prescribed burning in the context of the Kyoto Protocol.** Forest Ecology and Management. 251: 164-173.

Prescribed burning can be used to mitigate against catastrophic wildfires, which result in large releases of CO_2. Thus, prescribed burning can be considered a Kyoto-relevant means to reduce emissions countrywide. This study analyzes the potential for 33 European countries to reduce emissions through controlled burns. This strategy is particularly relevant for wildfire-prone countries. Results extrapolated from limited data indicate that on a continent-wide level, prescribed burning could reduce emissions by about 50 percent. This reduction is based on comparing 11 million tons CO_2 released from wildfire with 6 million tons released from prescribed burns; the latter strategy improves the likelihood that an area would not be burned by wildlife, but if it did burn, would release fewer emissions. However, the estimate in emissions "savings" is highly uncertain because the data set is limited and because it is difficult to quantify fuel consumption and emissions due to the unpredictable nature of wildfires.

154. Pacala, S.W.; Hurtt, G.C.; Baker, D.; Peylin, P.; Houghton, R.A.; Birdsey, R.A.; Heath, L.S.; Sundquist, E.T.; Stallard, R.F.; Ciais, P.; Moorcroft, P.; Caspersen, J.P.; Shevliakova, E.; Moore, B.; Kohlmaier, G.; Holland, E.; Gloor, M.; Harmon, M.E.; Fan, S.M.; Sarmiento, J.L.; Goodale, C.L.; Schimel, D.; Field, C.B. 2001. **Consistent land- and atmosphere-based U.S. carbon sink estimates.** Science. 292: 2316-2320.

It is estimated that the C sink in the Northern Hemisphere is 1-2 Pg per year, but the cause and spatial distribution of the sink are uncertain. This study clarifies how to make consistent direct comparisons between land and atmospheric-based sinks, that is, compare the same time period, land area, and set of biogeochemical fluxes. A summary table itemizes eight flux components that collectively create net atmosphere-to-ground flux, and includes a list and estimates from previous U.S. studies of C flux and related components. This study eliminates inconsistencies associated with constructing flux estimates for each of the eight components, and estimates a total sink of 0.30 to 0.58 Pg C/yr for 1980-89. One-half of component sinks are outside the forestry sector.

155. Piussi, P.; Farrell, E.P. 2000. **Interactions between society and forest ecosystems: challenges for the near future.** Forest Ecology and Management. 132: 21-28.

This paper provides a broad overview of the ways in which Europeans have interacted with, influenced, and managed forests throughout history and in the modern era, and discusses how shifting socioeconomic conditions affect current management, including C outcomes. The second half of the paper is devoted to illuminating future research needs.

156. Povellato, A.; Bosello, F.; Giupponi, C. 2007. **Cost-effectiveness of greenhouse gases mitigation measures in the European agro-forestry sector: a**

literature survey. Environmental Science & Policy. 10: 474-490.

This paper analyzes the cost of various agricultural and forest-based offsets and concludes that the most economically viable forest-based offsets result from forest management. Afforestation and bioenergy utilization are not as economically viable due to opportunity costs related to alternative land uses. These findings are similar to U.S.-based economic evaluations of agriculture-forestry mitigation costs.

157. Pregitzer, K.S.; Euskirchen, E.S. 2004. **Carbon cycling and storage in world forests: biome patterns related to forest age.** Global Change Biology. 10: 2052-2077.

This wide-reaching synthesis draws together data on NPP, NEP, and five forest C pools (living biomass, CWD, organic soil horizons, soil, and total ecosystem) for forests in three biomes (tropical, temperate, and boreal) to produce information on productivity and variability within separate age-biome specific combinations. With minor exceptions, all C pools increased as stand age increased in all biomes. Carbon storage and cycling dynamics are closely related to stand age in all biomes (age plays a large role in variability of NEP). Additional research is needed on C cycle dynamics and the interaction of forest age and disturbance history.

158. Rice, C.W. 2006. **Introduction to special section on greenhouse gases and carbon sequestration in agriculture and forestry.** Journal of Environmental Quality. 35: 1338-1340.

This introduction to the "3rd USDA Symposium on GHG and Carbon Sequestration in Agriculture and Forestry," is broad overview of the contribution and mitigative potential of agriculture and forestry to GHG management.

159. Richards, K.R.; Stokes, C. 2004. **A review of forest carbon sequestration cost studies: A dozen years of research.** Climatic Change. 63: 1-48.

This study reviews the results of more than 36 studies on forest C economics from 1989-2001 and concludes that: 1) accounting inconsistency plagued the literature such that a ton of carbon did not always refer to the same quantity; 2) forest C storage capacity, both domestically and internationally, is substantial at relatively low cost (250-500 million tons in the United States at a cost of $10-150/ton of carbon; 2 billion tons per year globally) for the next several decades; 3) there are many co-benefits of forest-based C sequestration; and 4) leakage and other accounting issues must be addressed or terrestrial sequestration may not result in real gains.

160. Van Kooten, G.C.; Eagle, A.J.; Manley, J.; Smolak, T. 2004. **How costly are carbon offsets? A meta-analysis of carbon forest sinks.** Environmental Science and Policy. 7: 239-251.

This study provides a meta-analysis of 981 estimates to determine the cost of forest-based C offsets. Forest conservation is a relatively low-cost mitigation strategy, with average costs ranging from U.S. $46.62 - $260.29/ton C. Afforestation and agroforestry are relatively more expensive options among this type of offset. Costs generally are higher when alternative land-use opportunity costs are taken into account and marginal rather than average costs are used.

161. Volney, W.J.A.; Fleming, R.A. 2000. **Climate change and impacts of boreal forest insects.** Agriculture, Ecosystems & Environment. 82: 283-294.

The manner in which insect outbreaks and climate change interact with and exacerbate each other are described. A review of the literature associated with stand-replacing outbreaks in the boreal forests of Canada indicates that insect outbreaks can release 1.3 - 2 times the amount of C released through wildfires, and that positive feedback cycles associated with these outbreaks need be taken into account when formulating mitigation and adaptation strategies.

V. Policy Perspectives

162. Breshears, D.D.; Allen, C.D. 2002. **The importance of rapid, disturbance-induced losses in carbon management and sequestration.** Global Ecology & Biogeography. 11: 1-5.

There are significant risks associated with an over reliance on terrestrial sinks for climate change mitigation because the potential for rapid, disturbance-induced losses is rarely acknowledged. These risks become more extreme as climate change worsens, feedback intensifies, and the earth's systems approach potential tipping points. The extent to which global ecosystems are at risk for such rapid losses is discussed.

163. Chen, J.; Brosofske, K.D.; Noormets, A.; Crow, T.R.; Bresee, M.K.; Le Moine, J.M.; Euskirchen, E.S.; Mather, S.V.; Zheng, D. 2004. **A working framework for quantifying carbon sequestration in disturbed land mosaics.** Environmental Management. 33: S210-S221.

This paper provides a new framework that the authors recommend for future studies of net C exchange in disturbed land mosaics. Edge areas and related effects differ substantially different from inner landscapes and warrant separate consideration when the C dynamics of a landscape are assessed.

164. de Jong, B.H.J. 2001. **Uncertainties in estimating the potential for carbon mitigation of forest management.** Forest Ecology and Management. 154: 85-104.

This study quantifies the sources of C flux uncertainties and errors and related to the classification of land-use/land-cover types, estimation of C stocks within each land use/land cover, historical land use/land cover and associated baseline assumptions, and variations in parameter values used to calculate carbon fluxes. Inclusion of forestry into the CDM is recommended.

165. Depro, B.M.; Murray, B.C.; Alig, R.J.; Shanks, A. 2008. **Public land, timber harvests, and climate mitigation: Quantifying carbon sequestration potential on U.S. public timberlands.** Forest Ecology and Management. 255: 1122-1134.

This study provides a reference and basis for comparison for policymakers and forest managers considering C sequestration and associated economic potential of different harvest scenarios in the United States. Three simplified scenarios are considered: business-as-usual, complete elimination of harvesting, and a return to pre-1989 harvesting levels. The latter two scenarios resulted in increases and decreases, respectively, in forest C storage on the order of 50 percent. However, the study does not consider how the risk of wildfire or other disturbances affects these scenarios, or the extent to which calculations might be altered by incorporating biofuels. The economic value of sequestered C on public forests could exceed timber values should these forests participate in C markets.

166. Im, E.H.; Adams, D.M.; Latta, G.S. 2007. **Potential impacts of carbon taxes on carbon flux in western Oregon private forests.** Forest Policy and Economics. 9: 1006-1017.

The effects of accounting for C revenues and costs in forest management decisions on both industrial and NIPF lands in western Oregon are considered. Results show that C taxes increase rotation lengths and concentrate production on lands with higher productivity. Taxes also reduce consumer and producer surpluses, though producer surplus losses are partially offset by C revenues. The baseline and tax rate used strongly influences outcomes and landowner participation. Taxes could be a useful policy tool to spur greater terrestrial sequestration, though disturbance and leakage risks must be taken into account. These risks likely will increase as a result of increasing land-based C stocks.

167. Kirschbaum, M.U.F. 2003. **To sink or burn? A discussion of the potential contributions of forests to greenhouse gas balances through storing carbon or providing biofuels.** Biomass and Bioenergy. 24: 297-310.

This study emphasizes that although forests play an important role in the global C cycle, land-based sinks are subject to saturation and land management alone cannot mitigate the buildup of atmospheric CO_2 concentrations. Storage in wood products and displacement of fossil fuels through bioenergy use can have relatively small but meaningful impacts on overall atmospheric C concentration in the near-term; over time, substituting bioenergy for fossil fuel results in significant benefits.

168. McCarl, B.A.; Schneider, U.A. 2001. **Climate change: Greenhouse gas mitigation in U.S. agriculture and forestry.** Science. 294: 2481-2482.

The role of agriculture and forestry mitigation is delineated in three main categories: reduction of direct emissions; expansion of the terrestrial carbon sink; and production of products that substitute for fossil-fuel intensive ones. However, the model used (Agricultural Sector Model, including GHG; ASMGHG) focuses almost exclusively on management alternatives, tradeoffs, and economic impacts for agriculture, and does not explicitly address forest management activities, an important factor in C sink expansion.

169. Nabuurs, G.J.; Thürig, E.; Heidema, N.; Armolaitis, K.; Biber, P.; Cienciala, E.; Kaufmann, E.; Mäkipää, R.; Nilsen, P.; Petritsch, R.; Pristova, T.; Rock, J.; Schelhaas, M.J.; Sievanen, R.; Somogyi, Z.; Vallet, P. 2008. **Hotspots of the European forests carbon cycle.** Forest Ecology and Management. 256: 194-200.

Article 3.3 of the Kyoto Protocol mandates accounting and reporting with respect to afforestation, reforestation, and deforestation, but article 3.4 allows Annex I countries to decide whether to include forest management activities that increase sink strength and use these activities to partially meet GHG reduction requirements. Of 25 European countries, 17 elected to include forest management activities. This paper summarizes how certain forest management activities influence C pools and fluxes over various time scales and emphasizes the importance of local solutions and appropriate management that integrates goals and optimizes outcomes based on regional and local factors.

170. Noss, R.F. 2001. **Beyond Kyoto: Forest management in a time of rapid climate change**. Conservation Biology. 15: 578-590.

This study suggests forest management practices that can help create and restore ecosystem and biodiversity resilience in an era of rapid and unpredictable change. Key among these are protecting primary forests, maintaining and creating connectivity, creating reserve buffer zones, practicing low-intensity forestry and maintaining natural forests (avoiding conversion to plantations), and preserving and maintaining keystone species, diverse gene pools, and natural fire patterns.

171. Pacala, S.; Socolow, R. 2004. **Stabilization wedges: Solving the climate problem for the next 50 years with current technologies.** Science. 305: 968-972.

This paper describes a toolbox approach to solving the climate crisis that includes 15 approaches, each of which would reduce emissions by 1 Gt C/yr. To reach climate stabilization by 2054, society would need to adopt and implement a total of seven wedges. Two stabilization wedges are related to agriculture and forestry: conservation tillage applied to cropland globally and halting tropical deforestation along with establishing 300 million ha of new tree plantations. Each wedge could reduce emissions by 1Gt C/yr.

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APPENDIX

Table A1.—Units of measures and conversions

Unit of measure	Explanation
Mg (Megagram)	= 10^6 grams = 1 metric ton = 1 tonne
Mt (Megaton)	=10^6 tons = 1,000,000 tonnes
Tg (Teragram)	= 10^{12} grams = 1 million metric tons = 1,000,000 tonnes
Pg (Petagram)	= 10^{15} grams = 1 billion metric tons = 1,000,000,000 tonnes
ha (hectare)	= 2.471 acres
Mha	= million hectares
ac (acre)	= 0.405 hectares

Table A2.—Names of chemical elements and compounds and their abbreviation

Abbreviation	Name
CO_2	Carbon dioxide
CO_4	Carbon tetraoxide
NO_2	Nitrous dioxide
N_2O	Nitrous oxide
N	Nitrogen
P	Phosphorous
K	Potassium

Table A3.—Acronym or abbreviations and their definitions

Abbreviation/ acronym	Term
ANPP	Aboveground net primary productivity
BT	Basal thinning
BOREAS	Boreal Ecosystem-Atmosphere Study (Canada)
CDM	Clean development mechanism
CERs	Certified emission reductions
CO_2e	Carbon dioxide equivalent; the amount of global warming potential generated, using carbon dioxide as a reference
CWD	Coarse woody debris
DOM	Dead organic matter
FACE	Free-air CO_2 enrichment
FFC	Forest floor carbon
FIA	Forest Inventory and Analysis, the name of a program within the U.S. Forest Service
FWD	Fine woody debris
GHG	Greenhouse gas
GPP	Gross primary productivity
IPCC	Intergovernmental Panel on Climate Change
MAI	Mean annual biomass increment
MCA	Multi-criteria analysis
NDVI	Normalized difference vegetation index
NEP	Net ecosystem productivity
NIPF	Nonindustrial private forest
NOAA	National Oceanographic and Atmospheric Administration
NPP	Net primary productivity
PES	Payment for ecosystem services
ppm	Parts per million
REDD	Reduced emissions from deforestation and degradation
RMS	Reclaimed mine soil
SEV	Soil expectation value
SOC	Soil organic carbon
SOM	Soil organic matter
SRR	Soil respiration response
TBCA	Total belowground carbon allocation
UNFCCC	United Nations Framework Convention on Climate Change

Table A4.—Scientific and common names of tree species referenced in the studies

Latin Name	Common Name
Abies alba	silver fir
Abies balsamea	balsam fir
Abies fraseri	Fraser fir
Acer spp.	maple
Betula alba	white birch
Betula pendula	silver birch, also known as European white birch
Carya cordiformis	bitternut hickory
Carya glabra	pignut hickory
Chamaecyparis obtuse	Hinoki falsecypress
Crytomeria japonica	Sugi (cedar)
Eucalyptus regnans	(Australian) mountain ash/swamp gum
Fagus spp.	beech
Fagus sylvatica	European/common beech
Fraxinus spp.	ash
Larix kaempferi	Japanese larch
Picea glauca	white spruce
Picea mariana	black spruce
Picea rubens	red spruce
Picea sitchensis	Sitka spruce
Pinus banksiana	jack pine
Pinus contorta	lodgepole pine
Pinus elliotti	slash pine
Pinus pinaster	maritime pine
Pinus ponderosa	Ponderosa pine
Pinus radiata	radiate pine
Pinus resinosa	red pine
Pinus rigida	pitch pine
Pinus sylvestris	Scots pine
Pinus taeda	loblolly pine
Platanus occidentalis	American sycamore
Populus deltoides	eastern cottonwood
Populus tremuloides	trembling aspen
Populus trichocarpa	black cottonwood
Pseudotsuga menziesii	Douglas-fir
Quercus spp.	oak
Quercus alba	white oak
Quercus coccinea	scarlet oak
Quercus robur	English oak
Quercus velutina	black oak
Tilia spp.	basswood
Tsuga heterophylla	western hemlock

The contents of the cd are available on the NRS Publications web page: http://www.nrs.fs.fed.us/pubs/34886

Hines, Sarah J.; Heath, Linda S.; Birdsey, Richard A. 2010. **An annotated bibliography of scientific literature on managing forests for carbon benefits.** Gen. Tech. Rep. NRS-57. Newtown Square, PA: U.S. Department of Agriculture, Forest Service, Northern Research Station. 49 p. [Includes CD-ROM].

Managing forests for carbon benefits is a consideration for climate change, bioenergy, sustainability, and ecosystem services. A rapidly growing body of scientific literature on forest carbon management includes experimental, modeling, and synthesis approaches, at the stand- to landscape- to continental-level. We conducted a search of the scientific literature on the topic of managing forests for carbon, and compiled an annotated list of citations. We chose to focus specifically on studies that addressed carbon in aboveground carbon pools, at both the micro (tree, stand) and macro (landscape, policy) levels. Aboveground pools include: live tree, understory, standing dead wood, down dead wood, and forest floor. The temporal scope of the literature search was the period 2000-2008 and the geographical scope was the temperate and boreal forests mainly in the United States, but also Canada, Europe, Russia, Japan, China, New Zealand, and Australia.

KEY WORDS: forest management, carbon sequestration, mitigation, climate change

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