

FINAL TECHNICAL REPORT – AUGUST 2, 2012

Title: Renewal of Collaborative Research: Economically Viable Forest Harvesting Practices That Increase Carbon Sequestration

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Introduction and Objectives

Forests provide wildlife habitat, water and air purification, climate moderation, and timber and nontimber products. Concern about climate change has put forests in the limelight as sinks of atmospheric carbon. The C stored in the global vegetation, mostly in forests, is nearly equivalent to the amount present in atmospheric CO₂. Both voluntary and government-mandated carbon trading markets are being developed and debated, some of which include C sequestration resulting from forest management as a possible tradeable commodity. However, uncertainties regarding sources of variation in sequestration rates, validation, and leakage remain significant challenges for devising strategies to include forest management in C markets. Hence, the need for scientifically-based information on C sequestration by forest management has never been greater.

The consequences of forest management on the US carbon budget are large, because about two-thirds of the ~300 million hectare US forest resource is classified as “commercial forest.” In most C accounting budgets, forest harvesting is usually considered to cause a net release of C from the terrestrial biosphere to the atmosphere. However, forest management practices could be designed to meet the multiple goals of providing wood and paper products, creating economic returns from natural resources, while sequestering C from the atmosphere. The shelterwood harvest strategy, which removes about 30% of the basal area of the overstory trees in each of three successive harvests spread out over thirty years as part of a stand rotation of 60-100 years, may improve net C sequestration compared to clear-cutting because: (1) the average C stored on the land surface over a rotation increases, (2) harvesting only overstory trees means that a larger fraction of the harvested logs can be used for long-lived sawtimber products, compared to more pulp resulting from clearcutting, (3) the shelterwood cut encourages growth of subcanopy trees by opening up the forest canopy to increasing light penetration. Decomposition of on-site harvest slash and of wastes created during timber processing releases CO₂ to the atmosphere, thus offsetting some of the C sequestered in vegetation. Decomposition of soil C and dead roots may also be temporarily stimulated by increased light penetration and warming of the forest floor. Quantification of these processes and their net effect is needed.

We began studying C sequestration in a planned shelterwood harvest at the Howland Forest in central Maine in 2000. The harvest took place in 2002 by the International Paper Corporation, who assisted us to track the fates of harvest products (Scott et al., 2004, Environmental Management 33: S9-S22). Here we present the results of intensive on-site studies of the decay of harvest slash, soil respiration, growth of the remaining trees, and net ecosystem exchange (NEE) of CO₂ during the first six years following the harvest. These results are combined with calculations of C in persisting off-site harvest products to estimate the net C consequences to date of this commercial shelterwood harvest operation.

Tower-based eddy covariance is an ideal method for this study, as it integrates all C fluxes in and out of the forest over a large ‘footprint’ area and can reveal how the net C flux, as well as gross primary

productivity and respiration, change following harvest. Because the size of this experiment precludes large-scale replication, we use a paired-airshed approach, similar to classic large-scale paired watershed experiments. Measurements of biomass and C fluxes in control and treatment stands were compared during a pre-treatment calibration period, and then divergence from pre-treatment relationships between the two sites measured after the harvest treatment.

Forests store carbon (C) as they accumulate biomass. Many forests are also commercial sources of timber and wood fiber. In most C accounting budgets, forest harvesting is usually considered to cause a net release of C from the terrestrial biosphere to the atmosphere. However, it might also be possible for commercial use of forests to contribute to terrestrial sequestration of C. The objective of our research project is to determine whether shelterwood cutting regimes now being adopted in the commercial forests of Maine and other areas of the country can achieve these multiple goals.

Research Activities and Methods

Site Description

The Howland Forest research site is located about 35 miles north of Bangor, Maine (45° 12' N, 68° 44' E, 60 masl). Stands in this forest consist primarily of red spruce (*Picea rubens* Sarg.) and eastern hemlock (*Tsuga canadensis* (L.) Carr.), with lesser quantities of other conifers and hardwoods. The region is flat to gently rolling. Soils vary from well drained to very poorly drained glacial tills, acid in reaction, with low fertility and high organic composition. Mean annual temperature is +5.5 °C and mean annual precipitation is 1000 mm, distributed evenly throughout the year. A snowpack of up to 2 m is present from December through March.

Carbon stock changes with harvest

Mechanized harvesting of hardwoods and softwoods in the 150-hectare experimental area began in November 2001 and was largely completed by the end of February 2002. Throughout the harvest, the logging contractors provided information on wet mass (truck weights) of logs removed from the forest by species, and the destination of each load of wood. Logs of all species were subsampled for moisture content in proportion to their abundance – a total of 108 wood samples were collected during the harvest. Carbon removal was estimated by re-surveying the 48 biomass plots arrayed around the tower. The persistence of carbon in various harvest product fates was calculated using decay constants from the literature.

For down and dead wood (DDW) measurements, plots were established along six transects, where all DDW that was >0.5cm diameter was collected. For large pieces, DDW volume was estimated by measuring the total length and diameter at each end of the log and assuming it was a cylinder. Subsamples of the logs were removed (intact) for density determinations after drying at 60°C. All DDW was removed from the plots so that the same plots could be resurveyed after harvest to quantify DDW production (slash) resulting from the harvest.

Total biomass (live and dead, above- and belowground) was about 77 Mg C ha⁻¹ prior to harvest. Harvesting removed roughly 15 Mg C ha⁻¹ of wood as logs and created about 10.5 Mg C ha⁻¹ of detritus (slash), being roughly evenly distributed between above- and belowground slash. According to the logging company, wood products created from the harvested material were divided roughly half and half into pulp products and sawlogs, to which we have assigned appropriate decay constants from the literature.

Slash production was quantified in several ways. First, the eleven DDW plots that had been cleared of material pre-harvest were resampled after the harvest. Second, the re-survey data from 48 biomass plots, along with species-specific allometric equations, were used to estimate branch, foliage, and

stump/coarse root detritus produced during the harvest. Third, six plots were established in logging tracks, where most of the slash was concentrated. Slash was removed from these plots, sorted into three size classes, weighed, and subsampled for moisture determination. These estimates of slash biomass were scaled up using estimates of total area covered by the logging tracks (based on track width and spacing). To estimate rates of decay of post-harvest slash piles, four slash piles of known initial mass were created by placing slash material onto screening (~2 x 3 m), and the entire pile was periodically reweighed.

Pre-harvest LAI was measured with a LICOR LAI-2000 along transects, holding the sensor level about 2 m above the ground. The 2001 measurements were made in August. Post-harvest measurements were collected mid-September to early October (pre-leaf fall) in 2002. Measurements (40) were made every 10 meters on each transect (12 transects) around the harvest tower. Litterfall was collected in ten litter traps (0.14m²) randomly distributed in two areas within the harvest – a “high impact” area that had been heavily disturbed by logging and a “low impact” area that had been minimally disturbed.

Soil respiration rates at three sites (same two sites as the litterfall measurements plus a third located within a very heavily impacted skid trail) were measured in the harvest area. Similarly, soil respiration has been measured routinely since 1997 in two plots within the footprint of the control tower site. At each site, eight PVC rings were driven into the ground about 1cm deep into the mineral soil. On each sampling date soil respiration was measured using a vented chamber and a LiCor 6252 infrared gas analyzer. Measurements were made approximately biweekly from May through November. Winter measurements were not feasible due to difficulty of access to the site. Estimates of soil respiration for the 6-month measurement period were determined by interpolation between measurement dates.

Water content of the mineral soil was measured using Campbell Scientific 616 water content reflectometry probes. Water content of the organic horizon was measured using 12 DC-half-bridge sensors.

We obtained tree diameter data from a series of increment cores taken from the southwest side of all trees >10 cm dbh in six of the biomass plots around the shelterwood and control towers. The total number of trees cored in the harvested and control areas were 138 and 180, and ranged from 18–34 per plot. Cores were obtained using a 4.3 mm Haglof Increment borer (Forestry Suppliers, Inc., Jackson, MS) in late October 2005.

Tree ring widths were determined using a Measu-Chron instrument (MMT micro-measurement technology, Bangor, ME), which consists of a dissecting microscope in conjunction with a digital positioner stage connected to a computer. Increments were measured to the nearest 0.01 mm starting with the last year of growth. Crossdating and measurement accuracy were checked using COFECHA. The ring width data were then converted into columnar files using the YUX.exe program and then imported into a spreadsheet.

The DBH recorded in the year of sampling and individual tree records of diameter increment allowed us to reconstruct the past diameters of essentially all trees on a plot. Forest tree carbon mass was calculated for each year by summing the biomass of all cored trees in a plot obtained from species specific whole-tree allometric equations and the reconstructed diameters. Carbon uptake was obtained by multiplying total tree mass by 0.5 and placed on a unit area basis by dividing by the plot area. Annual C uptake was obtained by difference between current and previous year plot C mass. This method may underestimate past C uptake by trees that are no longer standing on the plot. Recent mortality as evidenced by downed trees was not seen in the plots and our analysis here was restricted to only the most recent 10 years of diameter increment.

Eddy covariance measurements at the harvest site used a LI-COR Li-6262 closed-path infra-red gas analyzer and Applied Technologies sonic anemometer powered by a 320-watt solar panel and deep cycle battery storage system.

Results and Discussion

Carbon stock changes with harvest

The shelterwood harvest removed about 30% of the basal area. Harvesting removed roughly 15 Mg C ha⁻¹ of wood as logs and created about 10.5 Mg C ha⁻¹ of detritus (slash), being roughly evenly distributed between above- and belowground slash. Harvest products were divided roughly half and half into pulp products and sawlogs.

Net ecosystem C exchange (NEE) and tree biomass growth

Net ecosystem CO₂ exchange (NEE) is the sum of all photosynthetic and respiratory processes in the ecosystem. In the 160-year-old forest stand, which serves as a “control” for the harvest experiment, the average C sequestration during the last decade was 210±50 g C m⁻² y⁻¹ (2.1 Mg C ha⁻¹ y⁻¹), although considerable year-to-year variation in sink strength is evident (Fig. 1 top). Although two-thirds of the basal area still remained, the shelterwood stand most likely became a slight source of CO₂ in the second year following the harvest, losing ~20 g C m⁻². In the following years C sequestration increased steadily in the shelterwood stand by about 40 g C m⁻² y⁻¹, so that by 2008, NEP in the shelterwood harvested forest was within the 95% confidence intervals (about 40 g C m⁻² y⁻¹) of the nearby unmanaged forest (Fig. 1). Partitioning the net ecosystem production into gross photosynthetic production (GPP) and ecosystem respiration (R_{eco}) (Fig. 1, bottom) indicated that in the unmanaged forest R_{eco} has declined on average by 25±10 g C m⁻² y⁻¹ (mean and 95% confidence interval, P<0.01). We previously speculated that high respiration in 1999 and subsequent years resulted from decaying branch litter caused by a severe icestorm in January 1998. Over the 2003-8 period, respiration appeared to decline by ~45 g C m⁻² y⁻¹ in the shelterwood harvest area (P~0.1), consistent with decomposition of finer harvest slash. Annual respiration in the shelterwood forest (2003-8) was ~210 g C m⁻² y⁻¹ higher than in the nearby unmanaged forest (P<0.01, paired t-test). The difference between the GPP of the two stands during this time was not significant.

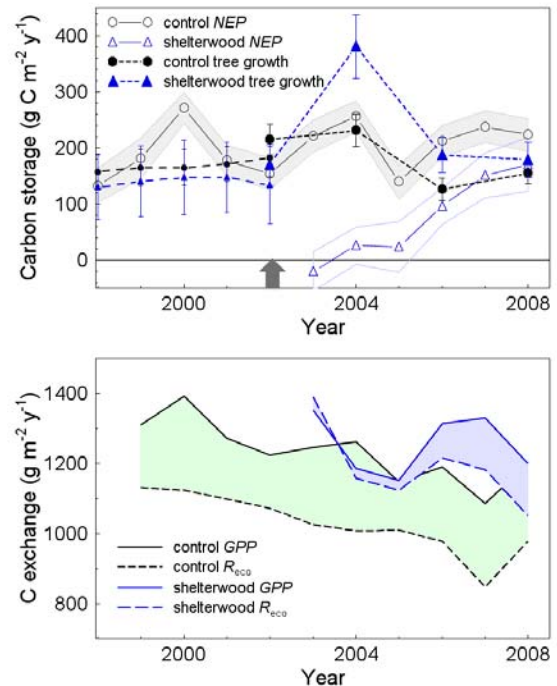


Figure 1. (top) C storage by trees and stands. (bottom) Partitioning of C fluxes between gross primary production and ecosystem respiration.

Storage in woody biomass prior to 2001 was calculated by reconstructing tree diameter chronologies from tree increment cores. The 6-year mean C storage rates in live biomass in the control (Fig. 1 top, small filled circles) and shelterwood harvest (Fig. 1 top, small filled triangles) stands were both about 160±20 g C m⁻² y⁻¹ prior to the harvest. Post-harvest C sequestration was calculated from the diameter change of trees in the inventory plots around the towers. Growth of the trees remaining after the shelterwood harvest accelerated in subsequent years. An important difference between the control and harvested stands is that, while NEP is greater than tree biomass C accumulation in the undisturbed forest,

tree C storage became greater than whole ecosystem C sequestration following the shelterwood harvest. This can only happen if other C pools within the harvested ecosystem, such as harvest slash, are simultaneously losing C.

Slash decomposition

Seven years post-harvest, the slash piles have lost about 60% of their mass (Fig. 2). When these measures of decomposition rates are extrapolated to the initial estimates of slash biomass produced during the harvest, we estimate that slash initially contributed about $0.4 \text{ Mg C ha}^{-1} \text{ y}^{-1}$ to ecosystem respiration, which helps explain why the harvest plot had lower *NEE* than the control forest, despite higher rates of tree growth (Fig 1).

Contribution of recruitment of young trees to C storage

Our inventory measurements suggest more small (<2") stems in the harvested plot compared to the control plot. To evaluate the contribution of these small stems to net C storage, we established specific seedling and sapling plots in our regular forest inventory plots in 2007. In the harvested stand, circular plots (4 m^2) were established around the plot center. In the control stand, we used larger (13.5 m^2) plots as there were fewer small trees. In each of the seedling plots, each stem was mapped and measured for tree height-class (required for use of allometric equations) and species.

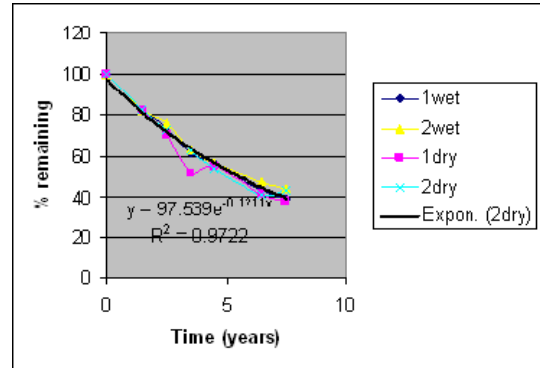


Figure 2. Harvest slash decayed returning CO_2 to the atmosphere in an exponential manner with a half-life of ~ 5.1 years.

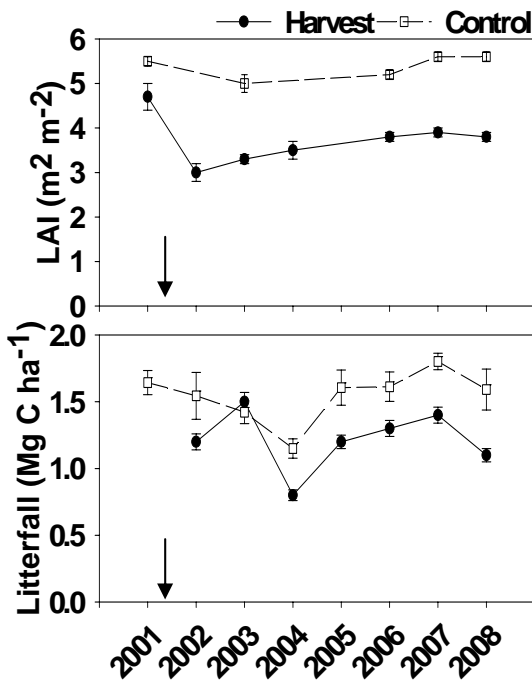


Figure 3: Leaf area index (LAI) and annual litterfall in harvest and control forest stands. Arrows indicate timing of the harvest.

In the harvested stand, small-tree biomass was 3.7 Mg C ha^{-1} , which is slightly less than 10% of tree biomass in stems $>2''$. In the control stand, small-tree biomass was about 1.0 Mg C ha^{-1} , which is $<2\%$ of live tree biomass.

Leaf-area index and litterfall

The harvest site had lower LAI values than the old-growth control forest (Fig. 3a). LAI dropped from pre-harvest values of about 4.7 to about $3.0 \text{ m}^2 \text{ m}^{-2}$ immediately after the harvest and then increased back up to about $4.0 \text{ m}^2 \text{ m}^{-2}$. Litterfall was variable among years in both sites (Fig. 3b), but with the exception of 2003, it remained lower in the harvest site compared to the control site. It is interesting that *NEE* has largely recovered (Fig. 1a) despite the fact that LAI and litterfall have not yet fully recovered (Fig. 3), which suggests higher light use efficiency for the harvested forest.

Soil respiration

Soil respiration rates were similar in the low impact harvest area and the unharvested mature forest sites (Fig. 4). In contrast, soil respiration was

significantly lower (repeated measures ANOVA) in the high impact and skid trail sites. These data indicate that reduced root respiration and inputs of C to the soil may have reduced soil respiration rates in the high impact areas, and that this effect must be larger than any stimulation of decomposition of soil organic matter that might have occurred post-harvest. This result is consistent with a recent literature review, indicating that soil C stocks tend to change very little following forest harvest operations. There appears to be a trend for a narrowing of differences among sites with time, indicating recovery of soil processes in the high impact sites.

Soil temperature and moisture

Soil temperature at 10cm was higher in the high impact site (Table 1). No significant differences in soil moisture have been found among sites (data not shown).

Foliar N, and ^{13}C

Foliar analyses of N concentrations and ^{13}C have revealed no significant differences between control and harvested stands. There was no significant difference in foliar N for hemlock (1.11% and 1.10% in the harvested and control stands, respectively), or for red maple (1.53% and 1.61% in the harvested and control stands, respectively).

To re-examine changes in foliar N during the first two years post-harvest, we established experimental plots in another nearby stand (Block A) that recently underwent the same shelterwood harvesting system. Again, we found no difference in foliar N concentrations of hemlock between harvested (1.20%) and control (1.22%) stands. We had hypothesized that the harvest could increase N availability and water availability to the remaining trees, which would cause an increase in foliar ^{13}C and foliar N concentration, but neither hypothesis was supported. Therefore, it appears that greater light reaching lower in the canopy and stimulating the growth of previously suppressed understory trees is the most likely explanation for increased growth rates.

Changes in water use efficiency

Another hypothesis to explain more rapid growth after harvest is reduced water stress. The decrease in basal area and LAI following harvesting would reduce evapotranspiration at the stand level, allowing the remaining trees to be less water-stressed and to leave their stomates open for longer periods, thus facilitating greater primary productivity. The eddy covariance data suggested that water use efficiency (WUE) has declined in the harvested stand. The ^{13}C in tree rings of the dominant species provides another measure of water use efficiency (Fig. 5). The

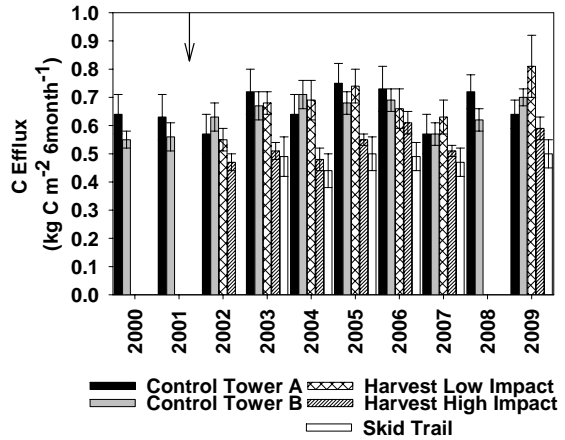


Figure 4. Soil respiration measured during the May–November sampling period at the old-growth control tower sites and at the shelterwood harvest sites. Note the reduced rates of soil CO₂ efflux in the high impact and skid trail plots of the harvested site.

Table 1. Average soil temperature at 10cm depth for June–Aug in high and low impact areas in the harvest site and in the control site.

YEAR	High Impact	Low Impact	High-Low Impact	Control
2003	16.9	15.3	1.7	
2004	16.3	14.7	1.6	
2005	15.2	13.4	1.9	15.6
2006	17.3	15.4	1.9	15.3
2007	15.9	14.3	1.6	14.2
2008	16.6	15.2	1.4	14.9

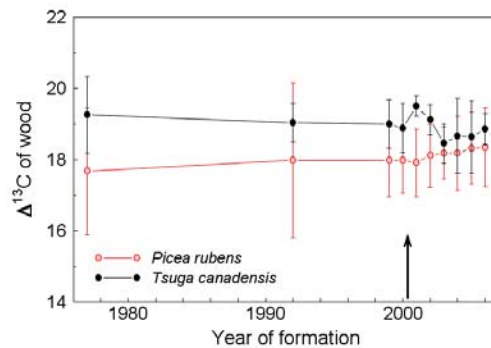


Figure 5. Tree discrimination against $^{13}CO_2$.

increasing ^{13}C discrimination (Δ) for wood taken from tree increment cores since the harvest in red spruce (*Picea rubens*) is consistent with a lower water use efficiency. The hemlock (*Tsuga canadensis*) response was more complicated; an initial increase in ^{13}C discrimination followed by a drop and then slow rise is consistent with a decrease, increase, and then slow decrease in WUE.

Net carbon gain/loss

Changes in estimated stocks of live tree biomass-C, harvest slash-C, and C in off-site harvest products are compared in Fig. 6a. Annual fluxes are shown in Fig. 6b, with uptake of C by trees shown as positive fluxes into the forest and emissions from slash shown as negative fluxes out of the forest. The live biomass decreased from a pre-harvest value of 77 MgC/ha to 52 MgC/ha post-harvest, and then increased up to about 64 MgC/ha in 2007 and 66 MgC/ha in 2008. The forest has been gaining C since the harvest, with good agreement between NEE and biometric measurements in 2006-2008, but not in 2003-2004.

We suspect that unmeasured fine needle loss from slash led to underestimates in the first few years after the harvest, which would account for an overestimate of net C fluxes into the forest relative to the measurements of NEE by eddy covariance. Of the 10 MgC/ha slash that was left on the site post-harvest, we estimate that about 6 MgC/ha still remained on site. Of the 15 MgC/ha or timber products exported from the site, we estimate that about 8 MgC/ha remain as wood products still in use. The live and dead biomass on site and the remaining timber products in use sum to 78 MgC/ha, which is within measurement error of the initial estimate of pre-harvest live biomass (77 MgC/ha). The total C stocks recovered to pre-harvest levels because the rates of forest regrowth were already exceeding decay rates of slash and harvest products, yielding an approximate C-neutral balance. This C balance will then become a net positive, as the remaining trees continue to grow faster than the decay of remaining slash and harvest products.

Net C consequences of forest harvest

Combining the off-site decay estimates with the on-site measurements of NEE, we can calculate the annual net C balance, which was initially negative, but turned positive in 2005 (Fig 6c). Hence, the combination of biomass of the regrowing forest plus the remaining storage of C in off-site harvest products nearly equaled the pre-harvest C stocks in the forest in 2007 (Fig. 6a).

We have compared these experimental results with some of the models currently used for evaluating regional effects of silvicultural practices on C balance, such as the Forest Vegetation Simulator (FVS) used by the USDA-FS. In collaboration with U. of Maine researchers, we have parameterized this model for Howland forest and then simulated the impact of different management practices on net C storage. The FVS model includes C storage in detritus (slash), and also wood products. None of the simulated management systems, including a shelterwood harvest, stored more C compared to the control treatments over 100 years. In contrast, our data show that the products from the harvest and the

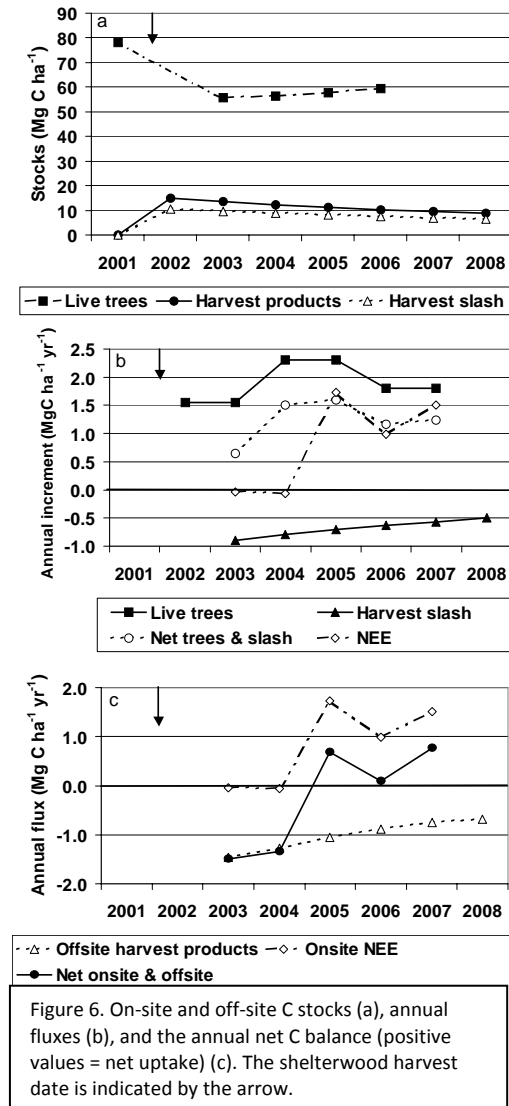


Figure 6. On-site and off-site C stocks (a), annual fluxes (b), and the annual net C balance (positive values = net uptake) (c). The shelterwood harvest date is indicated by the arrow.

subsequent forest regrowth of our experimental forest are already C neutral - i.e., the net C storage of on-site biomass and off-site products is about the same as before the harvest. This result suggests that parameterization of FVS may need to be further revised.

We also used the PnET CN model to investigate potential C and N cycling impacts of the shelterwood harvest. We ran the model using monthly data based on 1996-2004 averages recorded at the main tower. We used default settings for spruce-fir forests, a 150 yr spin-up period, followed by either “no harvest” or “shelterwood” scenarios. The model predicts that the first harvest causes an immediate decrease in net ecosystem productivity (NEP) below the baseline no-harvest level, but NEP recovers within 5 y and exceeds that of the no-harvest level until the next harvest removal (Fig. 6). A similar pattern is seen for the second and third removals, but after the third removal, recovery is slower. Foliar N concentrations increases after each simulated harvest, but begin to decline by 40 y after the first harvest, dropping below the baseline of the no-harvest level because of N losses. Similarly, total wood biomass never recovers to the baseline no-harvest value. Interestingly, we did not observe the simulated increase in foliar N in our field observations.

We experimented with modifying the light transmission routine in PnET to account for the fact that penetration of light through the canopy is different following the harvest, because the canopy is no longer closed and continuous. Within a closed canopy, transmittance t can be approximated by Beer’s law, $t = \exp(-kL)$, where k is the extinction coefficient and L is the leaf area index. For spruce-fir forests, PnET assumes a closed canopy and uses a default value of $k = 0.5$. Other researchers have found that an extinction coefficient of 0.3 gives a better fit to transmittance data for thinned stands. We found, however, that using a value of $k = 0.3$ following harvest somewhat paradoxically increased, not decreased, canopy photosynthesis as predicted by PnET. The reason for this is that this approach essentially “creates” additional light at each layer of the canopy.

The failure of this approach motivated a measurement campaign in June 2007 to investigate clumping of the canopy foliage. We quantified a clumping factor using the Tracing Radiation and Architecture of Canopies (TRAC) method. Walking the main tower transect four times with TRAC, we obtained consistent estimates of the clumping factor (0.94 ± 0.01); estimates for the Block A harvested stand were somewhat more variable (0.89 ± 0.03). These values do not indicate as great a difference in clumping between the two stands as was expected, but they are in agreement with literature values. If differences in the clumping factor between the harvested and non-harvested sites are only 10%, then this may also be the upper limit of an over-estimate of canopy photosynthesis in the harvested stand when assuming a homogeneous canopy rather than a more realistically clumped post-harvest canopy in the PnET simulations (Richardson et al., 2011).

Summary

We carried out intensive on-site studies of the decay rates of harvest slash, soil respiration, rates of growth of the remaining trees, and net ecosystem exchange (*NEE*) of CO₂. We also tracked the fate of harvest products and have estimated their decay rates. Our results indicate that the rate of forest regrowth was been faster than expected based on existing models. The harvest operation had already become net-C-sink within five years of completion of the harvest. Our results also point to potential model improvements that may be required in order to predict the carbon consequences of other harvest scenarios. The outcome is a win-win situation that permits economically viable exploitation of the forest timber resources while also enhancing terrestrial C storage.

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- Scott, N.A. Keynote speaker, A3 Foresight Program, 2008 Workshop, Seoul, Korea Upscaling from plot-based carbon data to regional scale: Current status and perspectives. Seminar title: Quantifying the Impact of Management Practices on Carbon Sequestration in Forest Ecosystems. Feb. 2008
- Scott, N.A., D.Y. Hollinger, E.A. Davidson, C.A. Rodrigues, H. Hughes, J.T. Lee, A.D. Richardson, D.B. Dail. Changes in the net carbon balance following a shelterwood harvest at Howland Forest in central Maine seven years after harvest. Annual Fall meeting of the American Geophysical Union, San Francisco, CA., USA. Dec. 2009.
- Scott, N.A., M. McDaniel, C.A. Rodrigues, D.Y. Hollinger, J.H. McCaughey, A.D. Richardson. Contribution of dead-wood respiration to ecosystem respiration in two mixed broadleaf/conifer forests. Annual meeting of the Canadian Carbon Program, University of British Columbia, Feb. 2009.
- Scott, N.A. Invited Speaker, Queen's University Biomass workshop. "Expanding our concept of forest inventory – opportunities for the future." March 2009
- Scott, N.A., D.Y. Hollinger, E.A. Davidson, C.A. Rodrigues, H. Hughes, J.T. Lee, A.D. Richardson, D.B. Dail. Changes in the net carbon balance following a shelterwood harvest at Howland Forest in central Maine seven years after harvest. Annual meeting of the Canadian Carbon Program., Feb. 2010. Montreal, Quebec.