Running Head: Carbon fluxes from Bioenergy Harvests

Title: Multiple Determinants of Carbon Fluxes from Bioenergy Harvests in the U.S. Northeast

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Abstract

Understanding the greenhouse gas emissions implications of wood bioenergy in the northeastern U.S. will require accurate data on the post-harvest carbon (C) fluxes. However, relatively few studies have evaluated C fluxes and offsets using field data from actual bioenergy harvests. We assessed C fluxes among multiple pools from bioenergy harvests, including whole-tree harvesting (WTH). These harvests were compared to both harvests with no bioenergy produced and unharvested reference sites, using inventory data from 35 locations. The analysis included C transferred to wood products and emissions from energy (electricity, heating, or combined heat and power). We used non-parametric tests to compare changes in C pools between unharvested and harvested stands as well as percent differences in forest C pools, C in wood products, and emissions from energy between types of harvests. All types of harvests decreased aboveground live ($P < 0.0001$) and dead ($P < 0.001$) tree C, increased fine woody debris (FWD) C ($P < 0.0001$), and decreased total stand C ($P < 0.001$). There was no change in the downed coarse woody debris (DCWD) C pool ($P > 0.43$) post-harvest, indicating that foresters are leaving sufficient DCWD on site post-harvest. Overall, bioenergy harvests using WTH had less C transferred to wood products and more emissions released from bioenergy than the other two types of harvests, which resulted in a greater net flux of C ($P < 0.05$). A Classification and Regression Tree (CART) analysis determined that the type of harvest or amount of bioenergy generated were not the strongest predictors in the amount of C fluxed from the harvest, although WTH sites had a larger flux of C compared to non-WTH sites (both with and without bioenergy; $P < 0.001$). The type of skidder and the silvicultural treatment had the largest impact on the net flux of C. Although additional studies need to be completed to determine the net emissions of bioenergy harvesting over the long-term and at landscape scales, we recommend that bioenergy

harvests in the Northeast reduce their C impact by selecting smaller equipment, hand felling when possible, and leaving a portion of tree tops on site.

Key words: northern hardwoods; aboveground carbon; bioenergy harvest; fossil fuel offsets; whole-tree harvest

INTRODUCTION

The increasing concentration of carbon dioxide (CO_2) in the atmosphere **Error! Bookmark not defined.** is predicted to have significant detrimental impacts on climate (Trenberth et al. 2007). This has led to a growing interest in managing carbon emissions through mitigation measures, including: decreasing the use of fossil fuels; improving energy efficiency and increasing the use of cleaner, renewable fuels; and maximizing carbon (C) sequestration in forests (IPCC 2007). Forests have been a main focus of those C mitigation conversations (Hamilton et al. 2010) due to their large capacity to sequester and store C (Nabuurs et al. 2007). Some hypothesize that harvesting trees and using the wood in place of fossil fuels for energy production ('bioenergy') such as electricity, heating, or combined heat and power (CHP) could result in a net carbon benefit (Hall 1997, Kroetz and Friedland 2008).

However, the net C outcomes (i.e. emissions reductions vs. increases) associated with managing forests for bioenergy production remains uncertain. In the northern hardwood region of the northeastern U.S. a key consideration is that wood biomass harvested for energy applications is typically only one of several products supplied by a single logging operation. Thus, C-accounting needs to consider not only post-harvest C left on site in residual biomass and C fluxes into and out of the forest system, but also C transferred to wood products, the life cycle of those products, and finally fossil fuel offsets (Eriksson et al. 2007, McKechnie et al. 2011). Previous accounting studies (e.g. Manomet Center for Conservation Sciences 2010, Nunery and Keeton 2010, McKechnie et al. 2011) have been limited by a relative lack of empirical data from actual bioenergy harvests, requiring modeling assumptions about carbon fluxes associated with harvesting practices such as whole-tree harvesting (WTH) and increased removals of low grade material. In this study we seek to inform C accounting by reporting field data on C pools and fluxes immediately following bioenergy harvests in the northeastern U.S.

Effects of forest management on C pools

Despite the development of complex forest C accounting protocol under both the Kyoto framework (Nabuurs et al. 2007) and developing carbon markets such as the American Carbon Registry (American Carbon Registry 2010), California Action Reserve (California Air Resources Board 2010) and numerous methodologies accepted by the Verified Carbon Standard such as the *Improved Forest Management through Extension of Rotation Age* (Verified Carbon Standard 2010), some aspects of forest management effects on C dynamics remain in debate. At issue is how to rigorously account for in-situ C pools (above and belowground), C fluxes through the wood products stream, and the avoided emissions (i.e. 'offsets') associated with substituting wood for other building materials and fossil fuels (Eriksson et al. 2007).

Depending on the assumptions made about each of these and their relative weight in the C accounting, studies can come to very different conclusions about forest management. For instance, many papers have determined that less intensive harvesting practices result in the greatest net increase in C storage (Harmon et al. 1990, Harmon and Marks 2002, Swanson 2009, Nunery and Keeton 2010), whereas other studies have inferred exactly the opposite, stressing substitution effects (Eriksson et al. 2007, Davis et al. 2009).

In our view bioenergy harvests add to this accounting complexity because the effects on C fluxes remain uncertain. For instance, a critical variable is the extent to which bioenergy operations might result in increased C removals (sometimes termed 'C debt') through intensified harvesting practices, thereby increasing rates of post-harvest flux both into and out of the forest system. Similarly, accounting for fossil fuel offsets requires information about the types of fuels replaced, for which accurate data is not consistently available. In both cases, accurate accounting, and to some extent resolution of the on-going debate about forest bioenergy (Harmon and Marks 2002, Searchinger et al. 2009, McKechnie et al. 2011), will depend on the advent of real (rather than assumed or theoretical) data quantifying these fluxes and substitutions.

Quantifying the net C effects of forest management practices, including bioenergy harvesting, requires an understanding of forest C pools and flux pathways and rates. It also requires accounting for harvesting effects on stand structure. For example, harvesting typically results in fewer large trees and may result in less basal area in snags (Crow et al. 2002). It may disproportionally impact dead C pools by affecting the input rate, species composition, and size distribution of downed coarse woody debris (DCWD; Harmon et al. 1986). Removing sources of DCWD (i.e. snags), changing disturbance regimes, and harvesting dead material results in an altered path and decomposition rates of the remaining DCWD (Harmon et al. 1986). Although dead wood decomposes and thus emits C (Parikka 2004, Johnson 2009, Searchinger et al. 2009), the overall deadwood pool can accumulate C for long periods, provided input rates from log recruitment, and exceed outputs (Harmon 2001). Therefore, removing dead wood for bioenergy impacts this stored pool of C.

Harvesting reduces forest C stocks (Johnson 2009), with longer harvesting rotations (i.e.

less frequent entries) and more structural retention increasing average C storage over the long term (Liski et al. 2001). However, no management results in the highest C storage over time when the accounting is restricted to in-situ forest C and wood products (Nunery and Keeton 2010). However, this may only be the case when accounting for *in situ* forest C and wood products without including fossil fuel offsets and adding substitution effects can significantly change the accounting outcome. For instance, combining intensive harvesting and offsetting coal with bioenergy may result in the largest C stocks because large standing biomass are left in the forest stand for longer periods of time (i.e. longer rotations) and bioenergy is offsetting a high emission fossil fuel (Eriksson et al. 2007). In some cases, the starting condition of a site (e.g. bare ground vs. old growth forest), rather than treatment intensity, may have largest effect on C pools (Harmon and Marks 2002). As demand for wood bioenergy increases, understanding the C trade-offs involved in different forest management approaches, including silvicultural treatments (e.g. WTH) specific to bioenergy, will become increasingly important.

Carbon mitigation through bioenergy harvests

Some have assumed that bioenergy is 'carbon-neutral' because harvested C (later combusted and emitted as CO_2) is resequestered through forest regrowth (Kroetz and Friedland 2008). A developing literature has questioned many of the fundamental assumptions in this argument (Johnson 2009, Searchinger et al. 2009, McKechnie et al. 2011, Gunn et al. In press). However, important questions remain regarding the temporal dynamics of C fluxes associated with bioenergy use. One of these is the time frame over which an initial C 'debt,' or flux of C out of the system, might be compensated by a C 'dividend' achieved through fossil fuel offsets and forest regrowth (Manomet Center for Conservation Sciences 2010, McKechnie et al. 2011).

Another key consideration is how these dynamics will play out at landscape scales as a function of harvests scheduled or staggered across time and space (Gunn et al. In press). There are likely to be compensatory effects at landscape scales, possibly equilibrating C emissions and C uptake across multiple stands harvested at different time periods (new Figure?). However, assuming that an equilibrium condition is theoretically possible, there may nevertheless be a permanent flux of carbon off the landscape if overall harvesting intensity increases, resulting in net average landscape C storage lower than a business as usual baseline (new Figure?). Our study addresses this point using field data to determine whether bioenergy harvests are intensifying C removals.

The intensity of bioenergy harvests in the northeastern U.S. may vary considerably, including the area harvested, volume removed, and the type of material harvested. Currently, the main source of bioenergy in developed countries is primary and secondary wood product operations and can range in scale from small family-owned firewood harvesting to large industrial energy plantations (Lattimore et al. 2009). Bioenergy is more expensive than fossil fuels, wind, and hydro and it is not economically feasible to transport forest residues long distances (Eisenbies et al. 2009). Therefore, bioenergy material is typically generated from: thinning operations; residues and mill waste; bioenergy plantations and agro-forestry operations; and fuelwood gathered from urban areas (Lattimore et al. 2009). These can include harvesting tree tops, branches, small diameter stems, and may include pulp and saw logs if the market is favorable (Briedis et al. 2011). However, there has been increasing concern that rising demand for bioenergy will result in increased harvesting of dead wood and residues (Briedis et al. 2011).

Despite this concern, some bioenergy harvesting may improve stand stocking and stem quality by removing low grade material. For example, thinning from below (i.e. “stand improvement cutting), sometimes used for bioenergy harvesting, can increase volume production and C sequestration more than thinning from the middle or above (Hoover and Stout 2007). However, increased demand for bioenergy may result in more intense harvests, such as WTH, which can result in reductions of DCWD, large logs, and snags (Briedis et al. 2011). WTH is a silvicultural practice that includes the removal of all the aboveground biomass as whole trees (including tree tops) and can also involve the removal of residues (Johnson and Curtis 2001). This differs from stem-only conventional harvesting where only the stems are taken off site (Vanguelova et al. 2010). It is an economical and efficient way of harvesting residues including roundwood on upper tree stems (Briedis et al. 2011). In addition to wildlife habitat and invasive species concerns (Lattimore et al. 2009), WTH may result in a decrease in soil N and C, affecting long-term productivity (Vanguelova et al. 2010), while saw log harvests may increase soil N and C (Johnson and Curtis 2001). The effect of harvesting intensity on C sequestration is still uncertain (Davis et al. 2009).

In this study we evaluated the effects of a range of bioenergy harvesting types and intensities on post-harvest C storage and emissions fluxes. We accounted for *in situ* forest carbon including live trees, snags, DCWD, and fine woody debris (FWD), as well as wood products (processing emissions and initial storage), and fossil fuel offsets. These were quantified using empirical rather than modeled data, lending strength to our analysis by avoiding assumptions about types of energy use and product allocation. Data from partial harvests, representative of dominant silvicultural practices in the U.S. Northeast (Sader and Legaard 2008), were used to compare harvests without bioenergy to bioenergy harvests either with or without WTH.

The study objectives were to: 1) compare the effects of conventional harvests to bioenergy harvests with or without WTH on the immediate post-harvest C storage in the stand, wood products, as well as fossil fuel offsets; and 2) determine which site-specific (e.g. property size, pre-harvest volume, ownership, etc.) and operational (e.g. harvesting equipment, silvicultural prescription, end-use, etc.) variables have the strongest predictive power on net C outcomes of harvesting wood for energy generation. We expected that WTH harvests would result in less C remaining in aboveground live and DCWD pools than harvests without bioenergy or bioenergy harvests without WTH. However, we anticipated that these WTH harvests would have more volume going toward bioenergy than bioenergy harvests without WTH. We predicted that sites that were harvested solely for wood products (i.e. no bioenergy) would have more C transferred to wood products than both types of bioenergy harvests and that harvest type would be strongest predictor of net C outcomes.

METHODS

Study site

Our study area encompassed portions of the northern hardwood region of the northeastern U.S., ranging from eastern New York State to western Maine (**Error! Reference source not found.**). The climate is humid continental (i.e. moist temperate) with even distribution of precipitation throughout the year, cold winters, and warm to hot summers. This postglacial region includes plateaus, hills, and the Green, White, and Adirondack mountain ranges. Sediment deposits created fertile soils consisting mostly of the Tunbridge series of soils, which are well-drained, loamy soils. Vegetation in the study area are predominantly mature (50-100 years old), even or multi-aged northern hardwood or northern hardwood-conifer forests. Dominant species include *Acer saccharum* (sugar maple), *Fagus grandifolia* (American beech), *Betula alleghaniensis* (yellow birch), and *Tsuga canadensis* (eastern hemlock), with significant portions of basal area composed also of *Fraxinus americana* (American white ash), *A. rubrum* (red maple), and *Pinus strobus* (eastern white pine).

We identified a pool of 43 recently harvested candidate sites to which we applied selection and site-matching criteria; of these 35 met our requirements and were included in the study (Table 1). The selection criteria included the following: harvested within 3 years; naturally regenerated stands (no plantations); low to mid elevation (610 m maximum); moderate to high site productivity (sugar maple site class 1-3); and presence of an unharvested adjoining portion of each stand. We specifically excluded clear-cutting operations in our study because most harvests in the Northeast are partial harvests and structural retention considerations for clear-cutting are fundamentally different. Each harvested site was paired with an adjacent unharvested portion of the stand of similar ecological characteristics (i.e. overstory composition, structure, and history) as a reference for estimating pre-harvest conditions. Our study included sites that had been harvested for wood products in addition to bioenergy with and without WTH.

Using a standardized survey, we collected information about the ownership, certifications, management objectives, silvicultural treatments, harvesting and skidding machinery, physical characteristics, and other operational variables from the foresters who helped us gain access to the properties (Table 2). We collected information about who did the marking, season and year of harvest, area harvested, location of de-limbing, types and amounts of products generated, type of energy generated from bioenergy harvests (electric, thermal, or CHP), end user of bioenergy (e.g. schools, pulp and paper mill, electric power plant, etc.) and any other meaningful observations or information. In instances where there was more than one application or user of bioenergy from one site, we asked the forester to specify how much of the bioenergy volume went to each user.

Field data collection

We inventoried forest structure and composition with 4-7 variable radius prism plots (2.3 metric basal area factor) plots at each site. The plots were randomly placed using a random number table to establish direction (°) and location of each plot, ensuring adequate distance between sampled plots. Trees > 5 cm at breast height (1.37 m) were inventoried. We recorded diameter at breast height (dbh), species, and live or dead status. For snags, the decay class (ranging from 1-9) was recorded and the height measured using an Impulse 200 laser range finder (Laser Tech, Inc., Englewood, CO).

At the location of each prism plot, we also placed a fixed area plot centered on the same point. The center of the fixed area plot was the same as the location of the variable radius prism plot. We used the line intercept method (Van Wagner 1968) with transect lengths of 35.7 m and 25.24 m to inventory DCWD and FWD, respectively. Trees leaning below a 45 ° incline from the ground, at least 10 cm in diameter at point of intercept, and greater than 1 m in length were counted as DCWD. We recorded the diameter and decay stage (1-5) following Sollins (1982) for each piece of DCWD at the point of intercept. FWD was considered to be any limb between 2-10 cm diameter at intercept and at least 20 cm in length. The diameter and angle to the ground of each piece of FWD was recorded. Angles were recorded in 5 ° increments as required in the Woodall and Williams (2005) volume equations.

Data analysis

The inventory data were input into the Northeast Ecosystem Management Decision model, NED-

2 (Twery et al. 2005), to generate a suite of structural and compositional biometrics, including aboveground biomass of living trees calculated allometrically using the Jenkins et al. (2003) equations. The volume, biomass, and C content of the four pools (aboveground live, aboveground dead, DCWD, and FWD) were calculated as described below.

The volume of DCWD by decay stage was calculated for each site using the general volume equation from Woodall and Williams (2005), developed originally by Van Wagner (1968). DCWD biomass was calculated by multiplying the volume of each log by the specific gravity corresponding to decay stage from Harmon et al. (2008). Since the species of each piece of DCWD could not be determined consistently, a weighted average of the specific gravities (using Harmon et al. 2008) for each decay class was calculated based on % basal area (% BA) by species for all live and dead trees at each site. The C content in the DCWD pool at each site was then calculated by multiplying the total biomass by the following C values by decay stage: 0.499 (decay stage 1); 0.488 (decay stage 2); 0.486 (decay stage 3); 0.518 (decay stage 4); and 0.501 (decay stage 5) (Harmon et al. 2008). The average volume of FWD was calculated by taking the mean of the angles of each piece of FWD for each plot and using equations from Woodall and Williams (2005). The biomass and C content in the FWD pool at each site was calculated in the same manner as the DCWD. Since the decay stage and species of each piece of FWD was not identified, the average C content of the 5 decay stages (i.e. 0.498) was used for all pieces of FWD.

Finally, snag volumes at each site were calculated using Honer et al. (1983) species-specific equations. We used species-specific tapering functions from Honer et al. (1983) to convert from our dbh measurements to the 1.30 height for dbh assumed in the volume equations. Tapering functions for morphologically similar species were used in some cases as suggested by

Townsend (1996). We followed the protocol in Harmon et al. (2008) to calculate biomass and carbon content, converting to a 1-9 decay stage scale. For snags of unknown species, we generated a weighted specific gravity value based on the % BA of identified snags with the same decay stage as the unknown snag species.

Fossil fuel offsets and wood products

We calculated the net C from offsetting fossil fuels with bioenergy, flux of C from the creation of wood products, and the C transferred to wood products. The percent of harvested product that went to energy production was calculated based on volume. All product volumes were converted to cords by calculating the weighted average of metric tonnes/cord or applying a factor of 0.96 cords per thousand board feet (MBF) to convert MBF to cords (Ashley 2001). For harvests that produced bioenergy, the C fluxed from energy generation from wood and that saved from avoided fossil fuel emissions was calculated. The amount of fossil fuels, and therefore C, that was offset was calculated based on the type of energy that was generated from the harvested bioenergy. We only accounted for the carbon emitted from combustion and did not include the greenhouse gas emissions from harvesting, transporting, processing, and other external energy inputs.

The amount of bioenergy generated from each harvest was calculated using two methods, depending on available information. The weight of chips, as reported by the operational forester, was used when available. Otherwise, the volume of chips was calculated based on the total biomass harvested, multiplied by the reported % bioenergy by volume. The energy conversion factors for both wood biomass and fossil fuels were calculated for electricity, heating, and CHP (Table 3). The fossil fuel used for heating and CHP was assumed to be natural gas, which has a heating content of 0.12 GJ/gallon (California Air Resources Board 2010). Since emissions for a specific fuel source are the same per unit of energy generated, the total C fluxed depends on the efficiency of the system. For electricity, it was assumed that the bioenergy replaced the Northeast NEWE electricity grid (Table 3; Rothschild et al. 2009).

The C transferred to wood products was calculated based on the information supplied by the foresters at each site. When foresters could not provide records (e.g. mill receipts) of the percent volume for each type of product generated from the harvest, we converted the estimated weights of the products to volume. For our analysis we did not treat firewood as a bioenergy product because cordwood is a traditional product in the harvesting baseline we were comparing against bioenergy harvests. The C transferred to wood products was calculated on a per hectare basis to correspond with the units of the emissions from energy generation. To calculate the total C stored and emitted during processing, we assumed that immediately post-harvest 61.4 % of the hardwood saw logs and firewood were in use, 56.9 % of the softwood saw logs were in use, 51.3 % of the softwood pulp, and 65.0 % of the hardwood pulp was in use, with the remainder emitted (Smith et al. 2006). The amount of C emitted from wood products is based on the life cycle curves for northern hardwoods presented in Smith et al. (2006).

We compared the C fluxed and stored in various pools between types of harvests. To compare harvested sites with their paired reference sites, we used a ‘percent difference’ metric modified from Westerling et al. (2006):

$$((x_1 - x_2)/\bar{x}_{1,2}) \qquad (1).$$

This metric was calculated for all fluxes and C pools and used to eliminate distorted or misleading values that can occur in % change or contrast data. For example, a change in biomass from 1 to 2 Mg/ha represents a 100 % change, but is small in absolute terms compared to a change of 100 to 200 Mg/ha (also 100 %). The percent difference metric normalized these relative contrasts (harvested vs. reference) across all sites, and thus provided a surrogate for estimating pre to post-harvest changes.

Finally, to calculate the net flux of C from each type of harvest, we used the following formula:

$$\overline{C}_{Flux} = \overline{C}_{Live} + \overline{C}_{Snag} + \overline{C}_{CWD} + \overline{C}_{FWD} + \overline{C}_{WPstored} - \overline{C}_{WPemitted} - (\overline{C}_{Bioenergy} - \overline{C}_{Offset}) \quad (2),$$

where WP represents wood products.

Statistical analysis

We choose non-parametric tests for our data analysis due to detected departures from normality for some variables. All statistical tests were performed in JMP 9.0.0 for Windows (SAS Institute Inc. 2010) and considered significant at $\alpha = 0.05$. To compare C pools between paired harvested and unharvested stands for each type of harvest as well as all the sites combined, we used the Wilcoxon Signed Rank test. Afterward, the Wilcoxon Rank Sum test with post-hoc multiple comparisons was used for all percent difference tests.

Lastly, we ran a multi-variate analysis in S-Plus 8.2 (TIBCO Software Inc. 2008) to identify the variables most predictive of net post-harvest C fluxes. We used a Classification and Regression Tree (CART) analysis to evaluate which variables contributed the most to determining post-harvest net C outcomes, both in remaining C stored in the stand and wood products as well as from fossil fuel offsets. CART is a robust nonparametric statistical method that partitions the variance (termed 'deviance') in a dependent variable based on categorical or numeric independent variables (De'ath and Fabricius 2000). It is a powerful tool for ecological analysis because of its ability to accommodate nonlinear relationships, high-order interactions, and missing values (De'ath and Fabricius 2000). The independent variables in our CART analysis and the number of sites for each classification are presented in Table 2. Of the 35 sites we inventoried, all generated saw logs and from those that generated bioenergy product, it was all in the form of wood chips. About half (46 %) of the harvests also produced pulp as a product, 28 produced firewood, 2 produced veneer, and 3 produced pallet. The percent bioenergy by volume (of total product) ranged from 5 – 99 %.

RESULTS

Effects of harvesting on forest stand C pools

Values for many of the carbon pools pre- and post-harvest ranged widely both within and among treatment categories (Table 4). Across all sites the largest pool of C was in the live trees, with a mean of 92.13 Mg C/ha (53.12 – 151.86 Mg C/ha) in the unharvested stands and 62.87 Mg C/ha (27.05 – 112.21 Mg C/ha) in the harvested stands. The snags comprised a very small portion of the total C on average, accounting for less than 7 Mg C/ha in the unharvested stands and 2.26 Mg C/ha in the harvested stands (mean of 1.82 Mg C/ha and 0.88 Mg C/ha, respectively). The DCWD pool, on average, held 6.25 Mg C/ha (1.41 – 14.78 Mg C/ha) in the unharvested stands and 6.98 Mg C/ha (1.04 – 15.41 Mg C/ha) in the harvested stands. The FWD pool held a mean of 1.26 Mg C/ha (0.59 – 2.30 Mg C/ha) in the unharvested stands and 2.09 Mg C/ha (1.02 – 5.52 Mg C/ha) in the harvested stands. Finally, the total mean C in the unharvested stands ranged from 68.83 – 159.95 Mg/ha, while it was 40.22 – 123.81 Mg/ha in the harvested stands. See Table 4 for mean C content (± SE) for each of the types of harvests.

Comparisons of C levels contrasting paired harvested and reference sites revealed differences for some aboveground pools (Table 5). There were significantly higher amounts of

C in aboveground live trees ($P < 0.0001$), snags ($P < 0.001$), and total C ($P < 0.0001$) in the unharvested stands than their paired harvested stands (Table 5). There was more C in the FWD pool post-harvest ($P < 0.0001$) compared to unharvested sites, but no statistically significant difference in the DCWD C pool (Table 5). Bioenergy WTH sites had a smaller snag C pool than paired unharvested sites ($P = 0.003$); however, this differnce did not hold for non-WTH bioenergy harvests (Table 5).

Statistical tests using the percent difference metric yielded a different perspective than those using absolute values. Comparing the percent differences in each of the forest stand C pools as well as the total change in stand C revealed no statistically significant difference between the three types of harvest ($P > 0.05$). However, our dataset showed evidence of wide variability among sites in terms of harvesting effects on C pools. Specifically, a Kruskal-Wallis test revealed that the variances between types of harvests were statistically significantly different from each other ($H = 12.00$; d.f. = 2; $P < 0.01$). This range of variability in percent difference was significantly wider (SD = 0.26) for bioenergy harvests with WTH than for the other treatments (no bioenergy SD = 0.14; bioenergy harvesting without WTH SD = 0.07). Since the Wilcoxon Rank Sum showed that the significant difference was between WTH and non-WTH sites, we combined the bioenergy without WTH and conventional (also no WTH). Comparing WTH to non-WTH sites showed that the WTH sites had a significantly larger total flux of C ($H = 11.87$; d.f. = 1; $P < 0.001$).

Emissions from energy production and C in wood products

All of the bioenergy produced from the harvests included in this study was derived from wood chips. Most of the bioenergy went to utility-scale bioenergy power plants around the Northeast

(83 %), some went to heat local schools (7 %), and the rest went to CHP at pulp and paper mills (10 %; Table 2). On average, bioenergy harvests using WTH produced about 51 % bioenergy by volume while bioenergy harvests without WTH produced only 10 %. This resulted in more emissions from energy generation, especially from electricity, than those from bioenergy harvests without WTH (Figure 2). The emissions from thermal energy generation (0.19 Mt C/ha) and CHP (0.58 Mt C/ha) were 106 % and 34 % less than those from electricity (20.71 Mt C/ha), respectively. We found a statistically significant difference between the types of bioenergy harvest based on the results of the Wilcoxon Rank Sum test. Emissions from bioenergy harvests with WTH were significantly higher ($P < 0.05$) compared to non-WTH bioenergy harvests. Since the bioenergy harvests using WTH yielded more biomass for bioenergy production than those without WTH, they also resulted in more savings from the avoided burning of fossil fuels (8.29 Mt C/ha for WTH sites versus 1.97 Mt C/ha for non-WTH sites; $P < 0.05$; Figure 2).

The bioenergy harvests that did not use WTH methods not only generated fewer emissions (7.15 Mt C/ha) from energy generation, but also left more C stored in the stand (103.42 Mt C/ha) and in wood products post-harvest (57.48 Mt C/ha) than bioenergy WTH sites (28.93 Mt C/ha emissions from bioenergy; 69.09 Mt C/ha in forest stand; and 14.84 Mt C/ha in wood products; Figure 2). Bioenergy without WTH had more C transferred to saw logs and firewood than either the bioenergy with WTH ($P < 0.05$) or no bioenergy harvests ($P < 0.05$). Although there was no statistically significant difference between C transferred to pulp for any of the harvesting categories ($P = 0.85$), the total C transferred to wood products and emitted from as a consequence of converting standing trees into wood products was significantly higher for bioenergy harvests without WTH than for WTH ($P < 0.05$).

Using the percent difference metric (Equation 2) yielded some statistically significant results between the types of harvests and the net C flux ($P < 0.001$). The mean percent difference in net C flux was -54 % for bioenergy harvests with WTH, -28 % for bioenergy without WTH, and -20 % for harvests with no bioenergy. Based on the post-hoc multiple comparisons, the significant differences can be attributed to contrasts between the bioenergy harvests with WTH and harvests without WTH ($P < 0.05$) and between the former and harvests that had no bioenergy production ($P < 0.001$).

In order to determine whether treating firewood as a wood product instead of bioenergy changed our results, we re-ran the statistical analysis with firewood as bioenergy without reclassifying our sites. The Wilcoxon Rank Sum test showed that the amount of C stored in wood products (without firewood) and emitted from the generation of those wood products was significantly lower for harvests without bioenergy than for bioenergy harvests without WTH ($P < 0.5$) or bioenergy harvests with WTH ($P < 0.05$). Furthermore, calculating the emissions from firewood with those from wood chip bioenergy resulted in no statistically significant differences between types of harvests ($P > 0.05$). This resulted in no statistically significant differences between the types of harvests for the percent difference analyses of the total net C flux ($P > 0.05$).

Influence of multiple predictors on C outcomes

The CART analysis did not select harvesting type (e.g. bioenergy vs. non-energy or WHT) as the best predictor of net C flux. Instead the analysis indicated that the strongest predictor for the sites we sampled was the type/size of skidding machinery (Figure 3). Specifically, harvests where a grapple skidder (e.g. John Deere 648H model) was used had a larger flux of C post-harvest than those employing a bulldozer/forwarder, a cable skidder (e.g. John Deere JD 540G-III model), and/or a grapple skidder. This is evident in the CART results, where skidder type was the top ranked predictor variable associated with the first partition of the dependent variable (Figure 3). Moving down the regression tree, two variables emerged as most predictive of the second tier partitions in total net flux of C. These were primary silvicultural treatment and type and felling equipment. The largest flux of C was associated with treatments including thinning from above, intensive single-tree selection, and shelterwood harvests, whereas thinning from below, small group selection, or treatments combining small group selection and thinning correlated with intermediate C flux levels (Figure 3). Felling equipment type also explained deviance in the total C flux post-harvest, at levels less than those associated with silvicultural treatment. Net C flux was more intense from harvests employing only a tree shear or mechanized harvester compared to harvests using only chainsaws (i.e. hand felling) or a combination of chainsaws and mechanized harvesting (Figure 3). The greatest overall net C flux was associated with the combination of grapple skidding and more intensive silvicultural treatments, whereas the lowest C fluxes occurred at sites with hand felling used in conjunction with cable-skidders, or bulldozers and forwarders.

DISCUSSION

Our study illustrates the influences on net C flux from bioenergy harvests, primarily WTH and type of equipment used. Although other researchers have explored the impacts of harvesting wood products (Harmon and Marks 2002, Swanson 2009, Nunery and Keeton 2010) and bioenergy (Eriksson et al. 2007, McKechnie et al. 2011) on net C flux using , our study is one of the first to use field data from bioenergy harvests. This previous research has shown that the type of wood material removed and the particular end-use significantly influences net C flux (Eriksson et al. 2007). Although Nunery and Keeton (2010) found that the harvesting intensity, including structural retention, and frequency impact both initial and long-term C storage, their study did not incorporate bioenergy. Our results and other research (Littlefield and Keeton In Review) indicate that the bioenergy harvests are highly variable in terms of both structural impacts and C emissions, and that the level of the impact depends more on the specifics of silvicultural treatment and harvesting/skidding machinery than the percent of harvested volume going to energy generation.

There was insufficient evidence in our dataset to conclude generally that an increase in bioenergy harvesting in the northeastern U.S. will result in an intensification of management with associated increases in net C fluxes. Instead the results tell a more nuanced story. The CART analysis clearly showed that operational variables, particular skidder size and type, were strongly predictive of net C flux because of the associated reductions in residual stand structure (i.e. increased C removals). These predictors, in turn, were positively correlated with WTH. Thus we can infer that, at least in some instances, bioenergy harvests will intensify C removals and net C fluxes, but the C outcomes will vary based on choice of operating machinery and silvicultural treatment specific to individual harvests.

Some researchers have argued that bioenergy harvesting practices, such as WTH, may result in a decrease of DCWD, large logs, and snags (Briedis et al. 2011). Although it is not economically worthwhile to transport forest residues long distances (Eisenbies et al. 2009), wood is perceived as a clean and renewable source of energy (Kroetz and Friedland 2008). The bioenergy market will drive the type of wood material that will be harvested. In our study, all types of harvests decreased aboveground live and snag C pools and increased the DCWD (except for a small decrease at the bioenergy with WTH sites) and FWD pool. Although bioenergy harvests with WTH had less C in snags and DCWD post-harvest, there was no statistically significant difference between the types of harvests and any of the C pools we measured. Due to the large variability within and between types of harvests, we cannot conclude, as a blanket statement, that all bioenergy harvests lead to increased removal of dead wood and residues. Rather, the wide range of variability suggested this outcome remains a possibility for all types of harvesting, and thus snag retention, or lack therefore, appears to be a more general issue.

In our study bioenergy harvests using WTH had the largest total net flux of C. This was due to less C being transferred to wood products and more emitted as bioenergy from this type of harvest. Wood products represent an important pool of C that can stay intact for decades if stored in materials such as furniture or construction grade lumber (Malmsheimer et al. 2008). Our results suggest there may be a trade-off between how much harvested volume from bioenergy harvests is allocated to wood products versus energy generation. However, our data did not support a conclusion that bioenergy harvests using WTH results in less C remaining in aboveground live trees and DCWD than bioenergy harvests with no WTH or harvests with no bioenergy. Although bioenergy harvests with WTH had lower snag C post-harvest, this result may indicate there is sufficient structural retention, which results in higher forest stand C storage than more intense harvests (Nunery and Keeton 2010). Furthermore, life cycle emissions may be higher if live trees are harvested for bioenergy instead of residues, such as tree tops and slash (Eriksson et al. 2007, McKechnie et al. 2011). Long-term modeling would be necessary to evaluate how the type of material harvested (e.g. volume of live and dead biomass) and amount of wood volume allocated to wood products and bioenergy affects long-term C balance (Schlamadinger and Marland 1999, McKechnie et al. 2011).

Variability between harvests

Our results suggest there is considerable variability between and within all types of harvests in the U.S. Northeast. Specifically, the fact that the type of harvest or the amount of harvested volume allocated to bioenergy was not the determining factor for net C flux implies variability in intensities of biomass. It also suggests variability in the allocation of harvested products to different end uses, including bioenergy, pulp fiber, and solid wood products. One indicator of why the average decrease in net C for WTH was larger (at -54 % as opposed to -20 % or -28 %) is that these harvests were more likely to use grapple skidders. Use of grapple skidders, in turn, resulted in a larger decrease in net C based on the CART results. At WTH sites 76 % used grapple skidders, while only 30 % of the non-WTH (both with and without bioenergy) used grapple skidders. These results show that harvesting method, intensity, and allocation of products most affects the total net flux of C immediately post-harvest.

Despite wide variation in harvesting approaches and site conditions, some clear trends emerged from our dataset. Although not statistically significant, conventionally harvested stands appeared to have more C in DCWD and FWD post-harvest than the bioenergy WTH stands. The bioenergy without WTH had the largest DCWD C pool and intermediate C storage in FWD post-harvest. At conventionally harvested sites, the total C in down woody material (DCWD and FWD) ranged from 5.4 – 8.0 % of total forest stand C at the unharvested sites and 10.9 – 13.2 % at the harvested sites. On average, down woody material, or lying dead wood, accounts for 1.7 to 4.6 % of total forest C in all forest types (Evans and Ducey 2010). This differs depending on forest type, with large ranges reported in the literature. Northern hardwood forests typically have 19.8-39.5 Mt/ha of DCWD (Gore and Patterson III 1986). This is an important pool of C that, besides holding C, performs other vital roles such as providing wildlife habitat, protecting soil erosion, enhancing soil moisture retention, cycling nutrients, and providing riparian functions (Harmon et al. 1986, Evans and Ducey 2010). The stands in our study had substantially higher C pools in DCWD and FWD than the 1.7-4.6 % range reported by Evans and Ducey (2010). From the harvests in our sample, it appears that many logging operations in the Northeast are either leaving adequate DCWD on site or are adding additional pieces during the harvest. However, for the FWD pool this was the case only for bioenergy without WTH.

Uncertainties in assessing impacts of bioenergy harvests

Research has shown the importance of assessing the impacts of bioenergy harvests over the long-term (Schlamadinger and Marland 1999, McKechnie et al. 2011). Some argue that burning wood releases the same amount of greenhouse gases per unit of energy produced as burning fossil fuels and that refining bioenergy releases more C than petroleum-based products (Searchinger et al. 2009). For this reason, the amount of C that needs to be sequestered over time per unit of energy produced may actually be greater for biofuels than fossil fuels (Manomet Center for Conservation Sciences 2010). These arguments imply that the long-term impacts of bioenergy harvesting are necessary to understand the length of the C debt then dividend.

The length of this C debt and dividend depends on the end-use of the bioenergy (Eriksson et al. 2007). Using wood for energy production, especially electricity, is not as efficient in terms of the amount of C released per unit of energy generated as using other fuels such as natural gas (Manomet Center for Conservation Sciences 2010). Furthermore, the more C that was initially on the forest stand, the longer it can take (through regeneration and C offsets) for the same amount of C to be restored to the landscape (Schlamadinger and Marland 1999). Although in our study the end-use of bioenergy included electricity, CHP, and thermal, most of the wood chips were allocated to electricity generation, there were not enough replicates of CHP and thermal to conduct a sensitivity analysis. This analysis of the total net C flux should also include the change in forest C stocks after harvesting (Johnson 2009, McKechnie et al. 2011).

Finally, our study attempted to quantify the effects of bioenergy harvesting in northern hardwood and mixed forest, but did not incorporate indirect emissions, such as harvesting, processing, and transportation. We only considered the immediate post-harvest C storage in the stand itself, wood products generated, and emissions from energy production, which only included the C emitted during combustion of wood chips or fossil fuels. However, indirect emissions only account for approximately 2-3 % of the total life-cycle emissions for bioenergy-derived electricity, heat, or CHP (Manomet Center for Conservation Sciences 2010). However, indirect emissions are much higher, at about ¼ of total emissions, for energy produced from natural gas. Performing a full life-cycle analysis and taking indirect emissions into consideration may result in a smaller gap between emissions from bioenergy or fossil fuels. However, the indirect emissions depends on many factors including the proximity of the fuel source (for both bioenergy and fossil fuels), the efficiency of the transportation vehicles, and many other external factors (Manomet Center for Conservation Sciences 2010). These many complex factors would result in additional assumptions needing to be made, creating uncertainty in the results. For this reason, only the actual C emitted from combustion of each type of fuel was used in the analysis.

Implications for bioenergy harvesting and C-accounting

Some researchers argue that atmospheric C reductions can be achieved in the long-term through sustainable forest management in combination with C transferred to wood products (Liu and Han 2009). In the short-term, similarly to McKechnie *et al*. (2011), we found that in all bioenergy harvesting scenarios, the C reduced in the stand and emitted from bioenergy energy generation was greater than that for equal amounts of energy produced from fossil fuels. In addition to considering the temporal scale, many researchers (Schlamadinger and Marland 1999, Searchinger et al. 2009, Manomet Center for Conservation Sciences 2010) have recently urged for a landscape C analysis of the effects of bioenergy harvesting on long-term C storage. A C analysis may only be relevant at the specified spatial and temporal scale and may give completely different answers depending on its scope (Harmon 2001).

Some research has suggested that longer harvesting rotations and less intensive harvesting, or no management at all, may have the greatest C benefit (Liski et al. 2001, Peng et al. 2002, Nunery and Keeton 2010). The finding that forest management did not affect net C flux is contrary to our findings, where this variable had the largest impact. Furthermore, although some believe that bioenergy harvesting can be increased in the Northeast for a C benefit (Kroetz and Friedland 2008), the long-term implications on atmospheric CO_2 concentrations must be considered. Understanding the implications of bioenergy harvests on the long-term net C flux will be vital in guiding informed energy policy.

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Table 1 – Site characteristics for live trees in unharvested stands including: NED-2 forest types; percent slope; elevation (meters), aspect (degrees), percent conifer of basal area (BA); total basal area (m^2/ha); quadratic mean diameter at breast height (cm); aboveground biomass (Mg/ha); and percent canopy closure.

Site ID	Forest Type	Slope (%)	Elevation (m)	Aspect (°)	Percent Conifer (% BA)	Basal Area (m^2/ha)	QMD (cm)	Above-ground live biomass (Mg/ha)	Canopy Closure (%)
1	Pine Hardwood	23.1	233	234	28.9	24.9	23.9	152.4	67
2	Northern Hardwood	12.3	248	221	7.9	28.9	21.6	185.7	87
3	Maple-Basswood	17.6	219	50	8.9	25.8	17.6	162.5	84
4	Oak Northern Hardwood	15.8	277	179	3.4	27.1	20.9	177.0	84
5	Northern Hardwood	24.9	596	30	10.7	32.1	16.7	202.5	95
6	Hemlock Hardwood	5.2	165	205	50.5	46.4	27.4	303.7	97
7	Northern Hardwood	10.5	439	96	9.6	33.5	17.7	217.5	94
8	Pine Hardwood	7.0	230	114	26.2	26.2	23.9	158.6	71
9	Hemlock Hardwood	14.1	155	245	43.5	31.7	30.0	213.9	83
10	Hemlock Hardwood	12.3	156	326	41.2	15.6	21.3	106.2	46
11	Northern Hardwood	10.5	244	183	5.5	31.6	19.0	189.4	88
12	Spruce-Northern Hardwood	21.3	407	26	52.1	33.5	16.1	205.1	86
13	Pine Hardwood	10.5	292	66	18.1	38.1	19.4	253.4	96
14	Hemlock Hardwood	0.0	306	139	66.7	41.3	27.2	244.7	89
15	Sugar Maple	48.8	538	53	1.7	26.6	21.0	206.4	88
16	Mesic Mixed Pine-Hardwood	3.5	209	39	10.9	31.6	18.7	187.6	93
17	Spruce-Northern Hardwood	19.4	467	156	43.9	23.5	17.1	123.1	69
18	Mesic Mixed Pine-Hardwood	3.5	377	147	3.2	28.5	21.8	202.0	91
19	Spruce-Northern Hardwood	14.1	385	265	17.6	19.5	19.7	114.8	59
20	Spruce-Northern Hardwood	8.7	438	280	9.4	29.4	18.1	189.1	80
21	Northern Hardwood	17.6	542	243	0.0	28.5	19.8	186.7	80
22	Northern Hardwood	12.3	422	212	0.0	26.4	21.7	185.3	88
23	Hemlock Hardwood	10.5	315	229	33.9	22.6	24.1	143.9	64
24	Northern Hardwood	19.4	542	189	4.7	29.4	25.1	190.3	89
25	Northern Hardwood	7.0	434	244	0.0	35.0	21.7	240.1	94
26	Beech-Maple	8.7	478	253	8.3	20.7	13.7	140.3	67
27	Hemlock Hardwood	23.1	135	47	49.2	37.3	22.8	218.2	93
28	Northern Hardwood	12.3	544	235	4.4	31.2	17.6	209.2	98
29	Pine Hardwood	10.5	269	240	27.6	34.9	20.7	203.8	86
30	Northern Hardwood	21.3	397	181	5.1	22.4	17.1	145.4	72
31	Northern Hardwood	19.4	393	75	0.0	23.9	20.6	171.3	81
32	Pine Hardwood	3.5	463	77	25.4	27.1	13.7	148.1	80
33	Mesic Mixed Pine-Hardwood	8.7	333	254	3.1	29.8	16.9	175.7	91
34	Spruce-Northern Hardwood	21.3	415	32	2.3	19.7	15.4	113.4	65
35	Northern Hardwood	14.1	601	223	3.3	28.0	18.6	182.2	93
	Mean	**14.1**	**361.83**	**N/A**	**17.9**	**28.9**	**20.2**	**184.3**	**82.4**

Table 2 – Independent variables used in the Classification and Regression Tree (CART) multi-variable analysis, their classification as categorical or numeric, levels if categorical, and number of sites for each classification. Certifications included in this study were: Northeast Organic Farming Association (NOFA; www.nofa.org/index.php); Vermont Family Forests (www.familyforests.org/); Tree Farm (www.treefarmsystem.org/cms/pages/26_19.html); and Forest Stewardship Council (FSC; www.fsc.org/). Other non-formal certifications included: Vermont Land Trust (VLT; www.vlt.org/); Biomass Crop Assistance Program (BCAP; www.fsa.usda.gov/FSA/webapp?area=home&subject=ener&topic=bcap); and easements held by the USDA Forest Service (FSE).

Independent Variable	Type	Levels	Number of Sites
Tenure	Categorical	public	6
		private	29
Ownership	Categorical	Family/Co-op	23
		State	6
		Corporate/Institutional	6
Certifications	Categorical	No: None, VLT, BCAP, FSE	23
		Yes: NOFA, VT Family Forests, Tree Farm, FSC	12
Current Use	Categorical	Yes	22
		No	13
Current Management	Categorical	sugarbush	7
		forestland	28
Marking by Professional Forester	Categorical	Yes	28
		No	7
Season of Harvest	Categorical	Summer	10
		Summer and Winter	4
		Fall	4
		Winter	17
Type of Harvest	Categorical	Bioenergy – WTH	25
		Bioenergy – no WTH	4
		No Bioenergy – no WTH	6
Primary Treatment	Categorical	thinning from above	8
		thinning from below	10
		single-tree selection	6
		shelterwood	4
		group selection	4
		uneven aged combo	3
Secondary Treatment	Categorical	thinning from above	2

		thinning from below	8
		single-tree selection	1
		group selection	4
		salvage logging	2
		scarification	2
		none	16
Skidder	Categorical	grapple skidder	15
		cable skidder	10
		both cable and grapple skidders	7
		none (bulldozer/forwarder only)	3
Cutting Equipment	Categorical	shear	20
		chainsaw	10
		shear/chainsaw	5
Chipping Location for WTH	Categorical	landing	25
		electric power plant	4
		N/A (no bioenergy)	6
Bioenergy (% by Volume)	Continuous	numeric	29
Buyer/End User of Bioenergy	Categorical	municipal	24
		municipal/schools	2
		municipal/pulp-mill or pulp-mill	3
		N/A (no bioenergy)	6

Table 3 – Energy conversion factor (GJ/tonne) for bioenergy (GJ/tonne) and fossil fuels (GJ/gallon) and emission factors (Mt CO_2e/GJ) for electricity, thermal, and combined heat and power (CHP).

Type of Energy Generated	Assumed Efficiency (%)	Energy Content (GJ)		Emission Factor (Mt CO_2e/GJ)	
		Bioenergy (per tonne)	Fossil Fuel (per gallon)	Bioenergy	Fossil Fuel
Electricity	30 [1]	4.80 [2]	N/A [3]	0.38 [4]	0.11 [5]
Thermal	80 [6]	12.80 [2]	0.09 [7]	0.14 [4]	0.08 [7]
CHP	55 (80 overall) [8]	8.80 [2]	0.06 [7]	0.21 [4]	0.12 [7]

[1] Midpoint of 20-40 % electricity efficiency (Demirbas 2001).
[2] Lower heating value of 16 GJ per dry tonne (50 % moisture) (Demirbas 2001).
[3] The Northeast (NEWE) grid is made up of various sources of fuel; therefore, one GJ/gallon value is not appropriate.
[4] Based on assumption that 50 % of the mass of wood is C (Birdsey 1992).
[5] NEWE eGrid emission factor (Rothschild et al. 2009).
[6] Direct combustion with 20 % loss (Demirbas 2001).
[7] Natural gas (California Air Resources Board 2010).
[8] CHP has 80 % overall efficiency: 30% efficiency for electric and 50% for heating.

Table 4 – Mean carbon content (Mg C/ha) in harvested and unharvested stands immediately post-harvest. The mean ± SE is shown in aboveground live, aboveground dead, DCWD, FWD, and total stand C for the 3 types of harvests.

	No Bioenergy no WTH		**Bioenergy with WTH**		**Bioenergy no WTH**	
Forest Stand	**Harvested**	**Unharvested**	**Harvested**	**Unharvested**	**Harvested**	**Unharvested**
Aboveground Live C	71.00 ± 10.85	96.03 ± 8.96	57.30 ± 3.12	86.73 ± 3.15	85.48 ± 4.84	120.04 ± 15.06
Aboveground Dead C	1.07 ± 0.31	1.86 ± 0.58	0.86 ± 0.15	1.56 ± 0.23	0.75 ± 0.25	3.41 ± 1.05
DCWD C	8.05 ± 1.11	5.33 ± 1.68	6.26 ± 0.52	6.44 ± 0.60	9.92 ± 2.03	6.52 ± 1.16
FWD C	2.35 ± 0.28	1.06 ± 0.10	2.00 ± 0.23	1.31 ± 0.10	2.15 ± 0.33	1.32 ± 0.10
Total Forest C	82.48 ± 10.65	104.28 ± 9.14	69.09 ± 3.49	98.10 ± 2.80	103.42 ± 4.95	142.75 ± 8.63

Table 5 – Wilcoxon Signed Rank test results for comparing paired harvested and unharvested stands for the 3 types of harvests for each of the forest stand C pools. The results for all the harvests combined are shown as well. The test for live tree, snag, and total carbon pools was one-sided, whereas the DCWD and FWD test was two-sided. The statistically significant results are indicated in bold.

		Live Tree	Snags	DCWD	FWD	TOTAL
	Test Statistic S	10.50	4.50	-5.50	-10.50	10.50
No Bioenergy no WTH	d.f.	5	5	5	5	5
	P-value	**0.02**	0.22	0.31	**0.03**	**0.02**
	Test Statistic S	162.50	96.50	6.50	-66.00	95.00
Bioenergy with WTH	d.f.	24	24	24	18	18
	P-value	**< 0.0001**	**0.003**	0.87	**0.01**	**< 0.0001**
	Test Statistic S	5.00	5.00	-3.00	-3.00	3.00
Bioenergy no WTH	d.f.	3	3	3	2	2
	P-value	0.06	0.06	0.38	0.25	0.13
	Test Statistic S	10.68	3.70	-0.93	-4.57	13.05
All Harvests	d.f.	34	34	34	27	27
	P-value	**< 0.0001**	**0.0002**	0.43	**< 0.0001**	**< 0.0001**

Figure 1 – Map of the study sites (*N* =35). Where two sites overlap due to close proximity, a '2' indicates that there are 2 properties sampled in that location.

Figure 2 – Total mean carbon (Mg C/ha) in harvested stands by harvest type. The C/ha is shown for: the measured forest stand pools; C transferred to wood products by wood product type; emissions from the generation of each of those wood products; emissions for bioenergy productions; avoided emissions from fossil fuel offsets. The error bars indicate total SE for the total forest C, wood products, and energy emissions.

Figure 3 – Classification and Regression Tree (CART) analysis on percent difference in total net C flux from unharvested to harvested sites. The CART ranks the independent variable based on predictive power with the variable that explains the highest amount of variance in the dependent variable on top. The size of the branch shows the amount of deviance explained by the independent variable at the top of the split and the length of the node illustrates the total sum of squares explained by the split. The independent variables used in the CART analysis are those from Table 2. Minimum number of observations used before split = 5; minimum node size = 10; minimum deviance required before split = 0.01; n = 112. In CART, n is calculated by multiplying the number of observations (n = 28) by the number of levels of the variable that explains the largest amount of variance (n = 4). Redrawn from S-Plus.

Figure 1

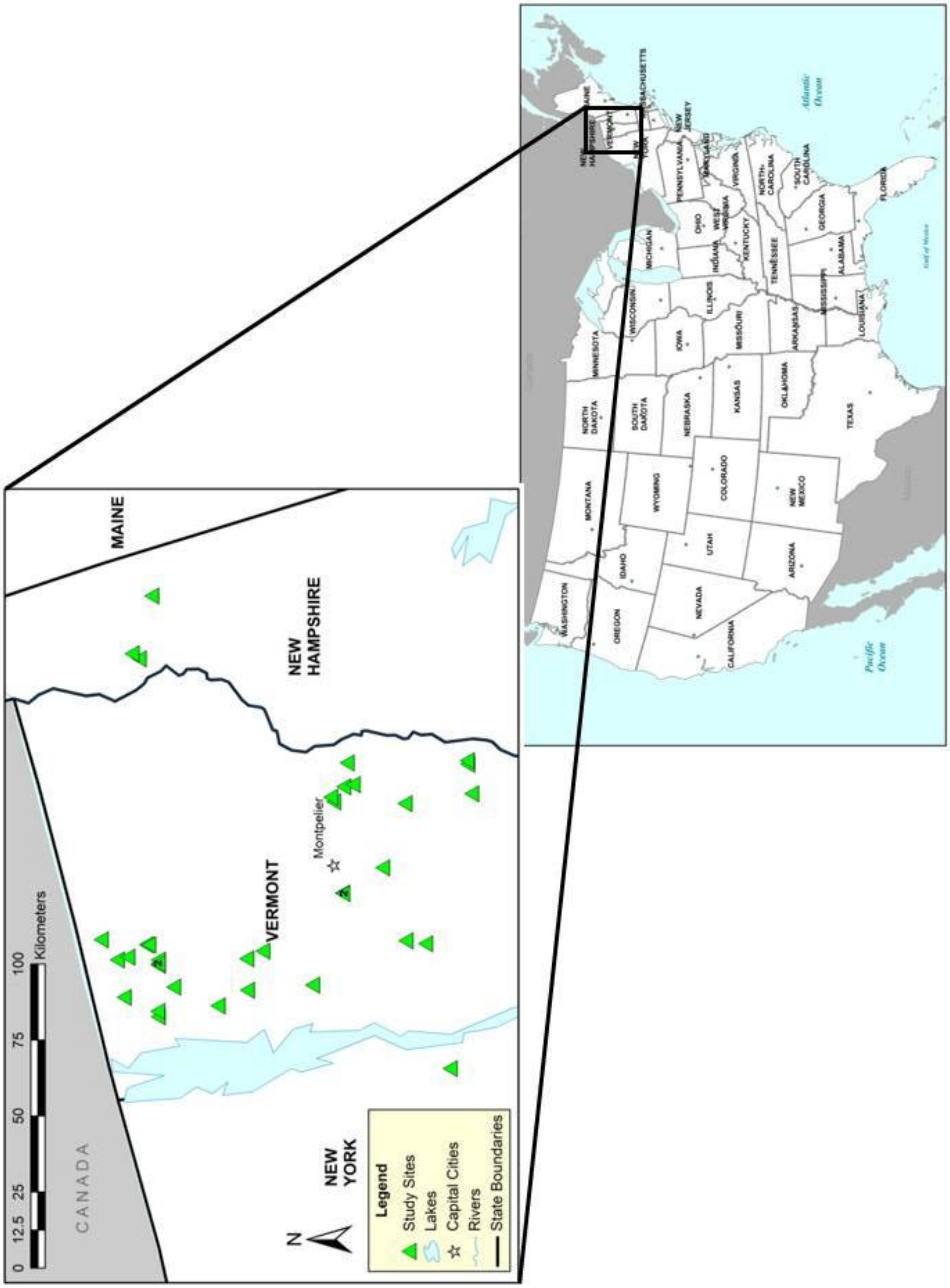

MAINE
NEW HAMPSHIRE
VERMONT
Montpelier
NEW YORK
CANADA
0 12.5 25 50 75 100 Kilometers
N
Legend
Study Sites
Lakes
Capital Cities
Rivers
State Boundaries
Atlantic Ocean
Pacific Ocean

Figure 2

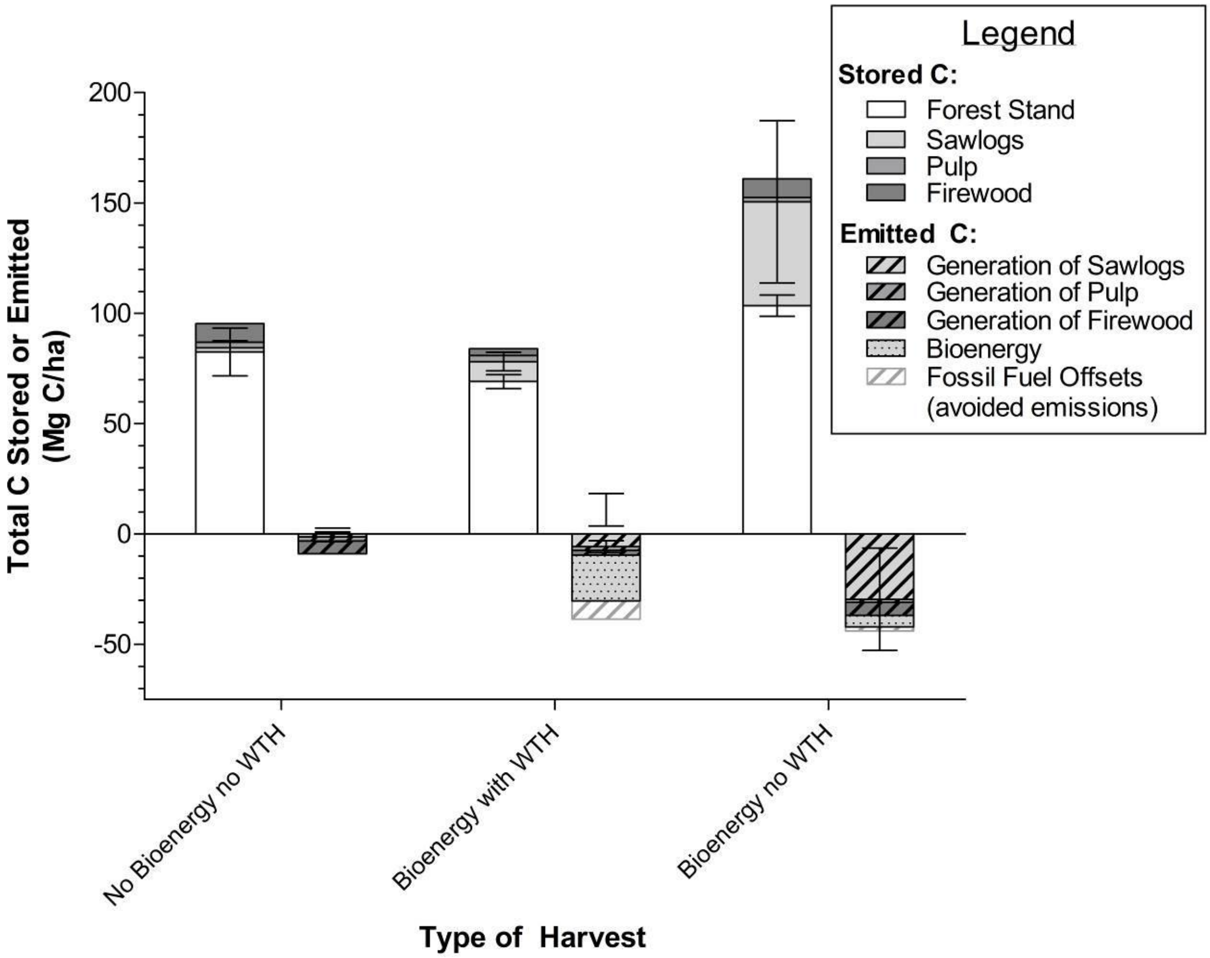
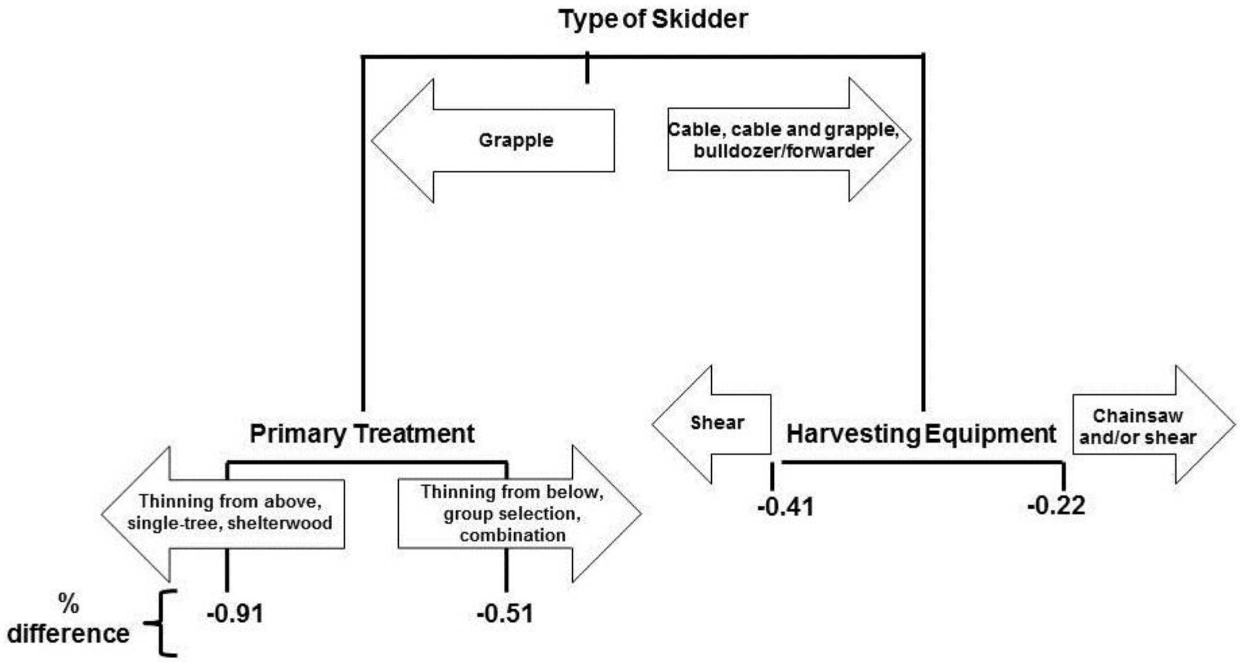

Legend
Stored C:
Forest Stand
Sawlogs
Pulp
Firewood
Emitted C:
Generation of Sawlogs
Generation of Pulp
Generation of Firewood
Bioenergy
Fossil Fuel Offsets (avoided emissions)
Total C Stored or Emitted (Mg C/ha)
200
150
100
50
0
-50
No Bioenergy no WTH
Bioenergy with WTH
Bioenergy no WTH
Type of Harvest

Figure 3


Type of Skidder
Grapple
Cable, cable and grapple, bulldozer/forwarder
Primary Treatment
Thinning from above, single-tree, shelterwood
Thinning from below, group selection, combination
-0.91
-0.51
Shear
Harvesting Equipment
Chainsaw and/or shear
-0.41
-0.22
% difference