Review

Harvesting carbon from eastern US forests: opportunities and impacts of an expanding bioenergy industry

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Abstract

There are ~10 Pg of biomass standing in forests of the eastern US, enough to meet the global liquid fuel demand, but it would take close to a century to recover habitat lost and the carbon that would be emitted to the atmosphere if all of this biomass were harvested. The amount of biomass that could be harvested sustainably from this forest biome is uncertain. Using past literature and previously validated models, we assessed four scenarios of biomass harvest in the eastern US: partial harvests of mixed hardwood forests, pine plantation management, short-rotation woody cropping systems, and forest residue removal. We also estimated the amount and location of abandoned agricultural lands in the eastern US that could be used for biomass production. Generating bioenergy feedstocks from partial harvests and residue removals resulted in greater carbon storage on the landscape relative to plantation management and short-rotation cropping. These lower-intensity harvesting practices require more land per unit of biomass removed than clear-cutting, but could avoid transferring carbon currently stored on the landscape to the atmosphere. At the landscape scale, some intensive harvesting (patch-cutting) may be sustainable if long-range management plans are used. If woody feedstocks were cultivated with a combination of intensive management on abandoned lands and partial harvests of standing forest, we estimate 176 Tg biomass y^{-1} (~330,000 GWh or ~16 billion gallons of ethanol) could be produced sustainably from the temperate forest biome of the eastern US. This biomass could offset up to 63 Tg C y^{-1} that are emitted from fossil fuels used for heat and power generation while maintaining a terrestrial C sink of 8 Tg C y^{-1}.

Keywords: biofuel, woody biomass, forest management, residue, logging, temperate forest, sustainability, CHP, greenhouse gas reduction, carbon dioxide emission, carbon sequestration

Introduction

Increasing demand for cellulosic feedstocks for biofuels and electricity generation has led to federal legislation that incentivizes both biomass removal from forests and cultivation of short-rotation woody crops (EPA 2011, USDA 2009). Woody biomass is an attractive feedstock because, in contrast to perennial grasses and annual crops, it is relatively compact and more easily transported and stored. It is also considered a more reliable source because wood can be harvested year-round and supplies are far less vulnerable than herbaceous feedstocks to adverse weather conditions (e.g. drought) in a given year. After European settlement in North America, much of the land that comprises the eastern forest biome of the US was cleared for agriculture, but many areas were later abandoned allowing forest re-growth. Widespread land-use change from agriculture to forests occurred following the Civil War and Great Depression while lands not in agriculture were heavily logged in the 1800s and early 1900s (Smith et al. 2002). The forest regeneration period that followed these events has resulted in increasing terrestrial carbon (C) stocks in the eastern US (Houghton 2003). Today, most forestland in the eastern US is privately owned and harvested at highly variable intervals. In fact, industrial forestlands represent only 11% of US forestland (Heath et al. 2010). Despite political mandates, there are many unanswered questions about the impacts on the environment and economy of intensifying the management of wood resources.

We investigated the resource potential and ecological impacts of harvesting biomass from different wood sources in eastern forestlands of the US. Even though the largest standing stock of forest C in the US is in the northwest, a recent meta-analysis concluded that the eastern US includes forests that are both the strongest sink of atmospheric C and the strongest source of forest C to the atmosphere in the nation, depending on location and management (Nave et al. 2010). The northern forest region, that includes both the northeast and Great Lakes region, is currently a net sink of 66 Tg C y^{-1} (C removed from the atmosphere) while the southeast is a net source of -7 Tg C y^{-1} emitted to the atmosphere (Nave et al. 2010). Immediate and complete harvest of eastern US forests (~10 Pg of standing biomass or ~5 Pg C; Turner et al. 1995) would not be sustainable because of the time required to recover C stocks (for example 5 Pg C / 66 Tg C y^{-1} = 76 y), habitat, and ecosystem services (water quality, recreation, etc.). Given that much of the region is a net C sink, an open question is: how much biomass can be harvested sustainably to offset fossil fuel demands?

Although the primary location for C sequestration (uptake) in most bioenergy cropping systems is in the soil (Zan et al. 2001, Lal 2004, Anderson-Teixeira et al. 2009), the C sequestration of forested systems in much of the eastern US is primarily in aboveground woody material (Schlesinger 1990, Richter et al. 1999, Schlesinger and Lichter 2001). Thus, wood resources are often managed with partial harvests where only a portion of the biomass is removed at any given time so that some aboveground biomass is always maintained. Low intensity (smaller percentage removed) and low frequency (longer time intervals between removals) harvests can result in less change to the C balance of a forest ecosystem (Davis et al. 2009, Nunery and Keeton 2010). Trade-offs between lower intensity harvests from the large aboveground C pool of forests and short-rotation systems that often store soil C (Sartori et al. 2006) have not been fully evaluated.

Residues from current forest management can provide an additional bioenergy feedstock source. In fact, forest biomass that is currently used for energy frequently comes from material that would decay quickly if left in the forest (e.g. logging residues) (Malmsheimer et al. 2008). Thus, forests that are managed for biomass alone or managed for both conventional wood products and biomass co-products may result in climate benefits (Van Deusen 2010, Seidle et al. 2007). Potential residue feedstocks include limbs and tops, small-diameter trees, downed logs, stumps, shrubs and litter/duff material that would otherwise remain in the forest after a timber harvest. Many of the current forest management guidelines, usually termed “best management practices,” do not provide definitive rules on the removal of these lower-value sources of woody biomass, in part because there are still many unanswered questions about the long-term effects of such extractions (Janowiak and Webster 2010, Evans et al. 2010).

Marginal and recently abandoned lands have been proposed as potential locations for cultivating biofuel feedstocks to avoid competition with high-yielding agriculture and forestry. There are varying definitions of marginal and abandoned lands but generally they are lands which cannot support economically viable production of row crops or intensive forestry because of soil quality, soil degradation or impractical location. Some wooded areas of the eastern US fit this definition (Campbell et al. 2008). Timber production in the southeastern US, for example, has been abandoned in some areas due to degraded soils and yield losses over time. These areas might support high-yielding perennial grasses and short-rotation woody cropping systems that are proposed as biofuel crops and also sequester soil C (Garten and Wullschleger 1999, 2000, Hansen 1993, Sartori et al. 2006, Zan et al. 2001). It is important for estimates of sustainability to distinguish between lands that are recently abandoned and abandoned lands that now support regenerated forests.

This study is the first to evaluate the sustainability of potential bioenergy production from eastern US forests based on demonstrated harvesting practices and measured land resources. There have been a number of recent works that describe environmental impacts of biomass harvest from forests within a state or a region (e.g. Buchholz et al. 2011, Manomet Center for Conservation Sciences et al. 2010, Evans et al. 2010). We rely heavily on previous literature for our analysis, but we synthesize these existing data to specifically address the potential for bioenergy production in the region that is the nation's largest terrestrial C sink, the eastern US (Nave et al. 2010, Xiao et al. 2011).

We evaluated four scenarios of biomass harvest in the eastern US using data from previously published literature and previously validated modeling tools that simulate biomass yields and C budgets. The scenarios range in management intensity to include (1) partial harvest from secondary forests in the northeast, (2) pine plantations in the southeast, (3) short-rotation woody crops in the Great Lakes region, and (4) residue managements across the entire eastern forest biome. We then estimated the potential biomass production on abandoned lands in the eastern US for each of these scenarios.

Methods

The scope of our review is constrained by assumptions about spatial scale, production chain boundaries, and temporal scales. Literature reviews of each scenario were conducted with a regional boundary defined, but model estimates reflect specific site-level C dynamics. Model simulations were used to illustrate temporal dynamics of C fluxes under a specific management practice. Environmental processes (e.g. biodiversity, water, habitat) affected by the spatial distribution of harvesting practices were not quantified. The boundary of the theoretical bioenergy production system evaluated in each scenario was limited to include only water inputs, nutrient inputs and harvesting practices that occur prior to processing biomass feedstocks for energy or fuel. The end use could be solid or liquid fuel. Logging equipment and transportation of biomass were considered only generally to distinguish between scenarios where biomass has already been transported (e.g. mill residues), scenarios with existing infrastructure to transport biomass (e.g. diversion of wood resources), and scenarios where new machinery and transportation demands would need to be met.

Overview of biomass production scenarios:

Scenario #1: *Partial harvest of biomass from secondary hardwood forests*

Secondary hardwood forests are managed with a number of different methods. Careful single tree selection cutting (that avoids “high-grading” or the selective removal of only the most valuable trees) is considered one of the most sustainable methods because it maintains species composition, forest biomass, and C sequestration over time (Schuler 2004). No fertilizers or irrigation are typically applied to the forest and very little management is required between harvest events. Specialized equipment and skilled labor are required to extract biomass at multiple entry points. In forestlands of the eastern US, this management is most common in the northeastern region (primarily in Maine, New Hampshire, Vermont, Massachusetts, Connecticut, Rhode Island, New York, Pennsylvania, and West Virginia).

Scenario #2: *Harvesting biomass from pine plantations*

There are active and abandoned pine plantations, many dominated by *Pinus taeda* (loblolly pine), across much of the southern piedmont and coastal plain (McNulty et al. 1996). These forests could be either reclaimed if abandoned or diverted from pulp and paper products to biomass production if active. Irrigation and fertilizer are sometimes used in this intensive management system that typically includes complete harvests every 12-20 years.

Scenario #3: *Short-rotation woody cropping systems*

Short-rotation woody crops are often comprised of poplar or willow species and can provide a consistent yield in a shorter turnaround time than pine plantations (3-13 y; Sartori et al. 2006). Fertilizer and sometimes irrigation are applied with this management practice and all aboveground biomass is removed at harvest. In the eastern US, this management is currently most common in the Great Lakes region (primarily in Michigan, Minnesota, and Wisconsin).

Scenario #4: *Forest residues*

Woody residues appropriate for bioenergy applications are created in a variety of operations. We defined forest residues to include logging slash (some bark, tree tops, limbs and leaves, etc.), thinning and tree removals associated with logging, clearing and fire treatments, or any other forest removals that are not directly associated with roundwood harvest (Conner and Johnson 2011). Primary mill residues are the bark and wood remainders resulting from mill processing of stem wood into products such as boards or paper, and include sawdust, trimmings, cores, and pulp screenings (Gan and Smith 2006). Secondary mill residues are remainders following the use of wood in construction, manufacturing and retail (lumber yards). Urban residues include municipal solid waste (pallets, yard waste, chipped wood), utility trimmings, private tree company trimmings, and construction and demolition wood (McKeever 2004).

Approach to Synthesis:

A literature review of empirical data was conducted to characterize management practices, nutrient requirements, C balances and growth rates for each of the biomass production systems described above. A general discussion about management costs and benefits was developed. Input requirements were reviewed and the response of biomass production to different inputs was quantified for each scenario.

We analyzed scenarios 1-3 over two time periods. A short-term boundary was set to 11 y to estimate biomass harvest through 2022 and the long–term boundary was set to 60 y. These timelines were chosen to correspond to policy mandates, i.e. Renewable Fuel Standard (EPA 2011), and the time it takes for abandoned land to reach a stage with late successional trees comprising half of the forest canopy (e.g. Drake et al. 2010), respectively.

After the initial evaluation based on scientific literature, we used the ecosystem models PnET (Aber et al. 1992, 1997; Ollinger et al. 1997, 2002; Davis et al. 2008) and ED (Moorcroft et al 2001, Albani et al. 2006, Medvigy et al. 2009) to simulate scenarios 1 through 3 in applicable regions of the eastern US. These modeling tools allowed us to estimate forest productivity dynamically while also partitioning wood production, soil C, and net C sequestration. Net C sequestration was further partitioned into photosynthetic C uptake, C losses through autotrophic and heterotrophic respiration, and C losses from harvested biomass.

The PnET model parameterization for scenario 1 (partial harvest from secondary forests) was based on previous work that calibrated the model for a mixed hardwood forest in the Fernow

Experimental Forest in Parsons, WV (Davis et al. 2008), and validated model estimates against hardwood forests with different harvesting histories (Davis et al. 2009). PnET has been used previously to estimate loblolly pine production in the southeastern US (McNulty et al. 1996, 1997), and thus we also used this model to simulate scenario 2. Parameterization of PnET for scenario 2 (pine plantations) was based on measurements made along a chronosequence of loblolly pine stands in the Duke Forest in Chapel Hill, NC (Drake et al. 2010).

The ED model has been used to estimate the yields and ecosystem service impacts of short-rotation cropping systems of hybrid poplar for the contiguous United States (Wang et al. 2010). ED was calibrated by combining a broad literature meta-analysis of *Populus* (poplar) ecophysiology with a data-assimilation approach for yield trials involving two clones and three planting densities at Rhinelander, WI (Strong and Hansen 1993). ED was then verified against observed data from six other sites (WA, MO, SD, WI, MN, ND) with 3-4 clones in each site (DeBell and Harrington 1997, Netzer et al. 2002). Model simulations for short rotation woody crops were based on a 4 y or 8 y rotation cycle at Mondovi, WI.

Abandoned agricultural lands were identified using historical land use data from the History Database of the Global Environment 3.0 (HYDE, 5-min spatial resolution) (Goldewijk et al. 2001; Goldewijk et al. 2007). Gridded maps from HYDE provided the fractional crop area and the fractional pasture area within each grid cell for each decade from 1700 to 2000. These maps were used to derive estimates of the amount of abandoned agriculture in each grid-cell (5 x 5 min) expressed as a percentage of area. To accommodate uncertainty in the contributions of transitions between crops and pasture to abandonment, we used upper and lower extreme estimates. The methods that produced these estimates are described in depth elsewhere (Campbell et al., 2008). Briefly, grid-cells undergoing abandonment were classified as grid-cells with decreasing agriculture over time. For the lower bound on estimates, concurrent increases in crop area and decreases in pasture area and vice-versa were considered transitions and did not constitute net contributions to the abandoned area. For the upper bound estimates, the area of abandoned agriculture was considered the sum of the area of abandoned pasture and abandoned crops which was then subtracted from the minimum areas attained across the time series. MODIS data were used to exclude urban areas from the analysis.

To calculate the area of abandoned lands in the eastern US, we intersected the boundaries of the United States with eastern coniferous and deciduous forest biomes from the World Wildlife Fund ecoregions (Olson and Dinerstein, 1998) to derive a 267.3 Mha estimate of the size of the forested biome in the eastern US. We then calculated the area of abandoned agriculture in this region using the assumptions described above. The amount of abandoned land was then estimated more specifically for the northeast, Great Lakes region, and the southeast so regionally appropriate scenarios of biomass production could be analyzed. Final estimates of potential biomass production were based on the area of abandoned land in each region and the wood production estimated for a given scenario.

Literature Review and Model Projections

Scenario 1 Literature Review: Partial harvest from secondary hardwood forests

Low intensity biomass management practices in forests (partial harvest of site, e.g. single-tree selection, diameter limit cutting or patch cutting of a landscape) do not require inputs of fertilizer or irrigation that are characteristic of many other agricultural systems. This is one reason that best management practices (BMPs), which are regulated at the state level and usually voluntary, point to lower intensity harvesting as a means to preserve water quality and other ecosystem services (e.g. Manomet Center for Conservation Sciences, 2010). The mean biomass removal for low-intensity diameter-limit cutting in mixed hardwood forests with mature sawtimber is ~17% of the total aboveground biomass (Schuler 2004, Davis et al. 2009, Buchholz et al. 2011). Although the harvest interval usually varies, 15-year intervals between low intensity harvests are common (Schuler 2004, Nunery and Keeton 2010).

Very few studies have evaluated the C sequestration associated with low intensity partial harvest management of forests. Of those that have evaluated partial harvests relative to other managements, most conclude that increasing harvest intensity has a negative effect on forest C sequestration (Balboa-Murias et al. 2006, Seidl et al. 2007, Davis et al. 2009, Nunery and Keeton 2010). These studies assume site-level comparisons where a partially harvested site, for example, is compared to a site that was entirely clear-cut (e.g. Davis et al. 2009, Nunery and Keeton 2010). These are informative for understanding harvest impacts, but must be evaluated in a slightly different context when considering landscape level processes. For example, at a landscape level, the impact of clear-cutting 17% of the forestland relative to denuding the entire landscape may be comparable to the difference estimated at the site-level between partial harvests and clear-cuts. Impacts of patch clear-cutting of larger woodsheds (the area that supplies a commercial wood mill) may be similar to partial harvests at the site-level, but patch clear-cutting requires long-term landscape planning to maintain aboveground biomass, C and community structure. Analysis of partial harvesting at the site level serves only as proxy for landscape dynamics.

It is also evident that net C storage depends on the end-use of biomass that is harvested from the forest (Ericksson et al. 2007, Seidl et al. 2007, Nunery and Keeton 2010). It has been estimated that biomass use for bioenergy results in greater CO_2 emissions than the use of biomass for wood products (Ericksson et al. 2007), mostly because wood products have a longer residence time than biomass that is immediately combusted for energy or heat. Thus, economic conditions and C residence times of harvested products can affect the sustainability of partial harvests from mature secondary forests (Nunery and Keeton 2010).

Scenario 1: Model simulation results

We simulated the partial harvest of a mature mixed hardwood forest on a 15 y interval using a version of the PnET model (Aber et al. 1996, 1997; Ollinger et al. 1997, 2002), PnET-CN_{sat} (Davis et al. 2008) which has been used to simulate different harvesting practices in the Fernow Experimental Forest, WV (Davis et al. 2009). The simulated forest is assumed to be unmanaged for 100 years prior to harvest simulations. We estimated annual wood production and net C sequestration assuming partial harvests with removal rates of 10%, 17%, 34%, or 51% of aboveground biomass. Only the removal rates varied, not the intervals between harvests. This allowed us to isolate the effect of increasing harvest intensity, although an interaction between harvest interval and intensity does exist. Net C sequestration included net biomass and soil accumulation as well as C emitted as a result of the final end use as bioenergy.

Modeled wood production in response to partial harvesting was maintained over a 60-year simulation period, with periodic fluctuations in response to harvest and climate variation (Figure 1a). Net C storage in forest biomass and soil increased over the sixty year period with 10%, 17%, or 34% biomass removal events, but the managed ecosystem only remained a net sink of C throughout the entire 60-y simulation period in the case of 10% and 17% removals (Figure 1b). Removals of 34% biomass resulted in a gradual gain of C over the long-term, but was still a net source of C to the atmosphere after 60 years. In contrast, removals of 51% caused the forest to be a net source of C to the atmosphere throughout most of the simulation period (Figure 1b).

Model simulations were parameterized for a forest in West Virginia, near the southern boundary of the northeast region, but the forest biomass estimated is comparable to that of forests in other parts of the northeast. The average biomass simulated before harvest was ~100 Mg ha^{-1}. Excluding Maine, which has a much lower mean merchantable biomass of 53 Mg ha^{-1} as a result of extensive management, the mean biomass reported for the other northeastern states is ~101 Mg ha^{-1}, ranging from 91 Mg ha^{-1} in New Hampshire to 115 Mg ha^{-1} in Connecticut, which has limited forest management (Buchholz et al. 2011). The level of active management of forests throughout the northeast varies widely, but responses to harvest that were estimated for West Virginia should apply to mixed hardwood forests across the region.

Scenario 2 Literature Review: Pine plantations

Fertilizers are often used in more intensively managed forestry production, i.e. plantations and short-rotation woody cropping systems. Irrigation is used infrequently (usually only at the time of planting) but sometimes supplements precipitation during periods of drought. We analyzed results from 24 forested sites measured in 13 independent studies of loblolly pine plantations in the southeastern US (Sartori et al. 2007, Albaugh et al. 2004, Coyle et al. 2008, Adegbibi et al. 2005, Jokela and Martin 2000, Ewers et al. 2000, Samuelson et al. 2003, King et al. 1999, Will et al. 2002, Borders et al. 2004, Cobb et al. 2008, Gresham and Williams 2002) to determine the effect of water (including both precipitation and irrigation), nitrogen (N), and phosphorus (P) inputs on biomass production. Using a 3-way ANOVA, we tested the effects of water, N, P, and the interactive effects of these variables on annual wood growth of loblolly pine plantations.

Based on literature, we found that annual wood growth was significantly affected by the interaction of phosphorus and water inputs ($p = 0.0320$) as well as the interaction of phosphorus and nitrogen inputs ($p = 0.0253$). The interactive effect of all three variables was not significant ($p = 0.1976$). If each variable was considered separately, the main effects of water and P were both significant ($p_{water} = 0.0396$, $p_P = 0.0345$; Figure 2) but the effect of N alone was not ($p = 0.1137$; Figure 2). Irrigation in managed loblolly pine plantations accounted for only 14% of total water inputs on average. Thus, P appears to be the most important input to loblolly pine plantations for increased growth, although the effect of P depends on N additions ($p_{pxn} = 0.0253$). The range of P and N that was applied in the studies analyzed here was 8 – 112 kgP ha^{-1} y^{-1} and 36 – 195 kgN ha^{-1} y^{-1}, respectively. This range describes experimental fertilizer applications and does not characterize the most common practices in pine plantations.

Scenario 2: Model simulation results

We simulated annual wood production and net C stored in pine plantations that were completely harvested at either 12 or 20 year intervals using the PnET-II version of the PnET model (Aber et al. 1996, 1997; Ollinger et al. 1997, 2002). PnET-II has been used to simulate pine production in the southeastern US (McNulty et al. 1996, 1997). The simulation assumed no manipulations of water, N, or P. Wood production was maintained at a mean of ~7 Mg $ha^{-1}y^{-1}$ during the three 20 y harvest cycles that were simulated over 60 years (data not shown), but wood production declined to a mean of ~4 Mg $ha^{-1}y^{-1}$ in response to the 12-year harvest cycles over the 60 year period (Figure 3a). This could be offset by nutrient additions, which, if optimized, could stimulate long-term production by up to 32% (Figures 2c, 3a). Without this nutrient supplementation, net C storage (including net biomass and soil accumulation as well as C emitted as a result of the final end use as bioenergy) declined over the 60 years in both the 12 and 20 year rotations (Figure 3b). In the near-term, the pine plantation was a sink of C, but the long-term perspective indicates that the system will become a net source of C to the atmosphere if harvests continue at a regular interval.

Noteworthy is that this scenario of a clear-cut plantation assumed that the same site was repeatedly and completely harvested at each interval. This should be distinguished from landscape-level patch cutting that uses clear-cuts at this frequency on only a small portion of the land while the remainder and majority is left un-harvested. In this landscape design, an individual land parcel can be un-harvested for ≥80 y between clearing events.

Scenario 3 Literature Review: Short rotation woody cropping

Fast growing broadleaf trees such as *Populus* spp. (poplar) and *Salix* spp. (willow) and inter-specific hybrids, are the most common species considered as short-rotation woody crops (Mitchell et al. 1992; Makeschin 1999; Weih 2004). In this system, known as short-rotation coppice, monocultures of these species or hybrids are planted, cut to the ground after 3-20 years, and then allowed to re-grow. Yields following coppice are typically much higher than in the first cycle, since re-growth is fueled from reserves in the root system. When considering areas that intersect with eastern US forestland, short-rotation woody crops are most common in the Great Lakes region. Because most data for this system has been collected outside of the eastern US, this section of our review first summarizes general observations of large scale field trials conducted in temperate zones of Europe and the Pacific Northwest, summarizing the main factors impacting yield. We then focus on the potential production and sustainability of short rotation woody crops specifically in the Great Lakes Region.

A review of historic data (available at the Biofuel Ecophysiological Traits and Yield Database (BETY-db) at www.ebi-forecast.igb.uiuc.edu), collected from 11 countries for poplar, and 5 countries for willow, indicated a wide range in yields of poplar and willow. Averaged globally, poplar and willow have a mean annual growth of 7.1 (n=663, sd=4.7) and 7.3 (n=349, sd=4.5) Mg $ha^{-1}yr^{-1}$, respectively. In the US, similar yields of 7.7 (n=277, sd=4.5) and 9.4 (n=68, sd=3.8) Mg $ha^{-1}yr^{-1}$ have been achieved for poplar and willow, respectively. The annual growth of poplar varied greatly across different climates, soils and also depended on the choice of clones and initial planting densities. In the northwestern US, annual growth ranged from 11.4 to 24.3 Mg $ha^{-1}yr^{-1}$ in 4-year-old poplar stands under different planting conditions (DeBell and Harrington 1997, Scarascia-Mugnozza et al. 1997, Heilman et al. 1994). The yield of 4 y old hybrid poplars in Puyallup, WA was 35 Mg ha^{-1} (Scarascia-Mugnozza et al. 1997). In the lower Midwest USA, poplar clones yielded up to 70 Mg ha^{-1} over 5 years (14 Mg ha^{-1} y^{-1}) without irrigation and fertilization (Dowell et al. 2009). There has been considerable recent effort to breed for sustainable higher yields in both poplars and willows, and a continued improvement in yield for this system should be expected (Aylott et al. 2008).

Although there are fewer examples of poplar and willow crops in the eastern US relative to other parts of the world, they are considered a potentially important biomass crop for the region (DOE 2006). In the Great Lakes Region, annual growth of poplar ranged from 3.5 to 12.8 Mg $ha^{-1}yr^{-1}$ (Strong and Hansen 1993, Netzer et al. 2002). Many poplar stands in the Great Lakes region are harvested at an older age (9 y) relative to those discussed above. Field trials of willow plantations have mostly been conducted in the UK to date, where the average annual growth is

8.1 Mg ha^{-1}yr^{-1} (Mitchell et al. 1999). There was however a willow trial in Tully, NY, where the annual growth was 16.3 Mg ha^{-1}yr^{-1} for a willow clone (SV1) in its fifth growing season (Kopp et al. 2001). Over a three-year period in the Great Lakes region, another willow clone (Sx-61) has an annual growth of 12.7 Mg ha^{-1}yr^{-1} (Randall et al. 2010). New hybrids of willow are currently being developed in the US for bioenergy and are expected to have even greater yields (e.g. Serapiglia et al. 2009).

Based on literature, we found that the annual growth of poplar and willow was positively correlated with annual precipitation and was not affected by N fertilization (Figure 4). Thus, water availability appears to be the key factor impacting production of poplar and willow crops. The range of N that was applied in the studies analyzed here was 50-336 kgN ha^{-1} y^{-1} for poplar and 10-336 kgN ha^{-1} y^{-1} for willow. Although there is no evidence that N has a significant effect on biomass production, N does reduce the time required to reach maximum production. Further, it seems unlikely that 50 Mg removals of biomass every 5 years could be sustained without N additions. Kopp et al. (2001) found that, with N additions of 336 kgN ha^{-1} y^{-1}, the cycle from cutting to harvest was reduced by one year in both poplar and willow. However, it is not clear that such extreme fertilizer additions are necessary to achieve this gain.

Scenario 3: Model simulation results

We simulated annual wood production and net C sequestration of poplar plantations in Mondovi, WI, that were completely harvested at either 8 or 4 y intervals using the ED model (Moorcroft et al 2001, Albani et al. 2006, Medvigy et al. 2009). ED has been validated against poplar production in multiple field sites in the Great Lake Region and also used to predict the annual growth of poplar for the 48 contiguous states of the US (Wang et al. 2011). The simulation assumed no manipulations of water, N, or P. Annual wood production in the first harvesting cycle was comparable to the observed mean yield of two poplar clones collected in a field trial established in Mondovi, WI (Netzer et al. 2002). If grown in 8 y cycles, the model simulations of net C storage (including net biomass and soil accumulation) were negative for the first 20 years and recovery occurred after about 3 harvesting cycles (Fig 5a). With a 4 y harvest cycle, the net C storage continued to decline over the 60 y period (Figure 5b). In the longer harvesting cycle, the poplar plantation was a net sink of C after about 25 years, but in the shorter harvesting cycle, the poplar plantation was as a net source of C to the atmosphere for the entire period of time tested. Carbon benefits will likely be increased with more recently bred high-productivity lines (Aylott et al. 2008, Serapiglia et al. 2009)

Scenario 4: Residues

Using data from the US Forest Service Timber Product Output reports, we calculated that eastern forests could supply over 118 Tg y^{-1} (Tg = 1 million metric tons) of residual woody biomass (Table 1, Milbrandt 2005). More than a third of residues (~47 Tg y^{-1}) are considered forest residues, material left on-site following tree removal. This consists mainly of standing deadwood, felled branches and stumps. The cost of retrieval and transport of this material could however be prohibitive unless harvest practices are combined with roadside chipping and compacting (Ralevic et al. 2010). The "practical" availability of such material is estimated by some to range from 40 to 60% (of forest residue) or 19 to 28 Tg y^{-1} given technical and cost constraints (Milbrandt 2005). Other estimates are much more optimistic with 26 to 37 Tg y^{-1} of recoverable forest residues from only the southern region of the eastern US (Conner and Johnson 2011). Despite costs, which depend on the residue type, transport distance, and end use, Gan and Smith (2007) estimated that the economic output of forest residues can be \$269 t^{-1} if residue biomass is used for electricity generation. Residues from primary mills, including bark, sawdust and trimmings, comprise over 40% of the total residue biomass (50 Tg y^{-1}), and availability of residues depends on the amount that is left unused by timber mills. Improvements in mill efficiencies and use of residues in on-site power generation have contributed to a steady decline in residue generation (Ackom et al. 2010); less than 3% of mill residues (~ 1 Tg y^{-1}) are considered currently "unused."

Urban woody biomass from tree trimmings, land development, and management of urban-forest boundaries contribute another possible 20 Tg y^{-1} of biomass from the eastern US. In 2002, 62.5 Tg of wood biomass was generated from construction, demolition, and landscaping wastes across the nation (McKeever 2004). A portion of this biomass (9.7 Tg) was recovered, demonstrating the feasibility of collection. Approximately half of the urban residue generated was left unused (McKeever 2004).

The role of urban residues in the portfolio of woody biomass for energy is possibly the least explored because this waste stream is often combined with estimates of organic municipal solid waste. The importance of this residue source is likely to continue to grow with population and urbanization. For cellulosic biofuel production, the major challenges will be identifying urban locations where sufficient residue is available for a commercially viable operation. Given the diversity of residue composition, it is less likely to be a suitable feedstock for biochemical production of ethanol, but would be more suited for combustion to provide heat and power (thermochemical conversion to fuels).

Residue production depends on management decisions that directly affect primary (non-residue) resources. Drivers that affect current biomass harvesting for timber, pulpwood and related mill activity will in turn affect the amount of mill residues that could be used for bioenergy. Increased demand for residues will likely result in higher prices and displacement of current alternate uses (Galik et al. 2009); however current policy such as the revised Renewable Fuel Standard (EPA 2011) will inhibit such market interactions.

Extraction of tree limbs and tops is not uncommon in timber operations, but the potential removal of small-diameter trees, downed logs, stumps, shrubs, litter/duff present challenges for management largely because methods for and the impacts of their removals have not yet been determined (Janowiak and Webster 2010, Evans et al. 2010). Foliage and branches contain higher concentrations of essential nutrients than tree boles and thus increased extraction of non-bole biomass may lead to a reduction in soil fertility (Janowiak and Webster 2010, Lattimore et al. 2009, Powers et al. 2005). Nutrient limitation is likely to be a greater concern in the southeast, where lands have been managed more intensively, and both N and P limitation has been documented in the forest (reviewed above). Nitrogen is often not limiting in the northeast and other nutrients deplete slowly. Analyses of nutrient budgets in the eastern United States have suggested that calcium is the nutrient most likely to experience gradual but long-term depletion (Janowiak and Webster 2010).

Effects on soil C and fertility appear to be highly site-specific and subject to management practices. For pine forests, several studies comparing stem-only, whole tree or complete tree harvests (removing slash and some forest floor components) had mixed results (Laiho et al. 2003, Johnson et al. 2002). While whole tree harvesting and removal of residues may negatively impact C pools at some sites, starting soil conditions, timing of harvest with weather conditions to prevent erosion, fertilization, understory competition, and tempered herbicide treatments with replanting can improve soil C (Laiho et al. 2003, Johnson et al. 2002).

Increased removals of residual standing trees (live and dead), as well as limbs and other harvest slash could also affect biodiversity. Clearly biodiversity of species that rely on decaying woody material will be affected by commercial slash harvesting. For example, diversity of non-vascular plants such as mosses, liverworts, fungi, and lichen (Caruso and Thor 2007, Astrom et al. 2005), as well as some invertebrates that rely on decaying litter material to lay eggs or as a food source (Nitterus et al. 2007), could be severely impacted. In contrast, ectomycorrhizae appear to be robust to residue removal or ash amendment (Hagerberg and Wallander 2002) and vascular sub-story vegetation may not be affected if soil conditions are maintained (Astrom et al. 2005). Specialists (organisms with more narrow metabolic requirements) are likely to be impacted to a greater extent than generalist species (Jonsell 2008, Nitterus et al. 2007). Selective retention of slash piles and stumps could mitigate these losses.

Abandoned Lands

We estimated that the area of abandoned agricultural land that is not currently in forest or urban development but is part of the eastern forest biome zone in the US was between 10.8 and 20.4 Mha (based on Campbell et al 2008). This is 4 and 8% of land in eastern US forest biome, respectively. In the last 15 y alone, 30.2 Mha of agricultural land was abandoned in the region but a significant portion of this land has been consumed by urban developments, leaving 16.6 Mha of non-forested abandoned lands. To place this in context, the largest single crop in the US, maize, currently occupies 40 Mha of the contiguous 48 states. A greater proportion of the land abandonment occurred in the southeast (8.83 Mha) relative to the northeast (3.84 Mha) and the Great Lakes (3.94 Mha) (Figure 7). The northeast region experienced greater agricultural abandonment in the 1800s and earlier in the 1900s. As a result, much of this area is now comprised of mature forests (>100 y old forest) with high species diversity, ecosystem services and recreational value. The exceptions to this are large areas of southwestern New York and eastern Maryland that have transitioned out of agriculture more recently.

Discussion and Conclusions

If all abandoned agricultural land and unmanaged forests were harvested according to the practices reviewed here, we estimate that 191 Tg (million metric tons) of wood biomass could be collected annually for bioenergy, but this management would be unsustainable due to a loss of -1.7 Tg C y^{-1} to the atmosphere (Table 2). By reducing the amount of land managed for pine plantations to 17% of abandoned land in the southeast (simulating a landscape-level partial harvest plan), we estimated that 176 Tg y^{-1} of wood biomass (~330,000 GWh electricity or ~16 billion gallons liquid fuel) could be harvested sustainably in the eastern US for bioenergy with an annual C sequestration of 8 Tg C y^{-1} (Table 2) over a 60 y time horizon. This could displace 63 Tg C y^{-1} from fossil fuel emissions if used for heat and power generation or 19 Tg C y^{-1} if used to produce ethanol. Five sources of biomass are included in this estimate: short-rotation woody crops in the Great Lakes regions, pine plantations in the southeast, partial harvests in the northeast, woody residues, and partial harvest of currently unmanaged and unreserved forests in all three regions.

In the Great Lakes region, there is a potential to harvest 32 Tg y^{-1} from short rotation woody crops planted on abandoned agricultural land and 0.43 Tg y^{-1} of biomass from unmanaged and unreserved forestland while maintaining terrestrial C sequestration (Table 2). This assumes that short-rotation woody crops could be cultivated on abandoned lands with 8 y rotations between harvests. In the southeast, 109 Tg y^{-1} could be cultivated in pine plantations on abandoned lands, but this would result in a gradual decline in terrestrial C stocks (Table 2). Partial harvest of currently unmanaged and unreserved forestland in southeast could yield 1.45 Tg y^{-1} of biomass. Using only partial harvests in the northeast region where much of the forest is mature and there is less recently abandoned land, it would be possible to harvest 4.35 Tg y^{-1}

(Table 2) while maintaining forest C stocks and habitat, but only 0.36 Tg would be immediately available because time must be allowed for forest regeneration on the abandoned land parcels. Finally, woody residues can yield 119 Tg y^{-1} across all three regions (Table 1, 2).

Literature review and temporally dynamic simulations of woody feedstock production clearly demonstrate differences among the four harvesting scenarios in their capacity to produce bioenergy feedstocks, to offset CO_2 emissions, and consequently to address climate change mitigation. Low intensity biomass management of secondary hardwood forests, via partial harvests (10-17% removals), results in greater C sequestration relative to more intensive harvests (>34% removals) and C uptake is maintained over both the short-term (11 y) and long-term (60 y) time periods that were analyzed (Figure 1). Plantation management and short rotation woody crops result in gains or losses of C to the atmosphere depending on the harvest rotation interval and the duration of the practice. Pine plantation management results in a net sink of C in the short-term (11 y), but this practice becomes a net source of C to the atmosphere over the long-term (60 y). Short rotation woody crops are a net source of C to the atmosphere in the short-term but this practice becomes a net sink of C over time with 8 y harvest intervals (Figure 5). The initial soil disturbance for planting results in a release of C, but long-term growth eventually exceeds respiratory losses.

Woody residues represent a large proportion of the available biomass feedstock (67%) in the eastern US. The majority of woody residues from eastern forests are produced through active logging and milling activity in the southeast. In this region, eleven states produce roughly half the woody residue material in the US. This is the only region in the U.S. with projected continued growth in timber harvesting (Gan and Smith 2006). International competition, especially in the pulp market, has depressed some mill activity but growing markets for bioenergy pellets as a result of the 2008 Farm Bill and the E.U. Renewable Energy Directive may be drivers for growth, at least in the near-term. In contrast, the availability of wood and wood residues in the northeastern US appears to be limited by social factors, mainly associated with landowner attitudes which tend toward minimal management of secondary forests and the lower economic activity in the forest sector relative to the southeast (Butler et al. 2010). If partial harvest or short rotation woody crops were adopted in the northeast and Great Lakes regions, some additional woody residues would be generated that are not included in the estimates provided here.

Sustainability targets for bioenergy

In bioenergy management, there are four kinds of sustainability that must be considered: climate change mitigation, environmental sustainability, economic sustainability, and energy security. Inevitably there are tradeoffs that do not allow all four aspects of sustainability to be maximized simultaneously. Our results directly inform objectives related to climate change mitigation and environmental sustainability (in C storage, 1 unit C = 3.67 units CO_2), but we can further interpret the results in the context of current harvest costs and legislation to also address economic and energy security sustainability.

Although terrestrial C sequestration can be a large sink, climate change mitigation requires more holistic strategies that are not limited in scope to simple manipulations of C. Nitrogen and P management, for example, can have important implications for not only production and C sequestration but also for GHG emissions associated with manufacturing fertilizer. Application of fertilizers could boost C sequestration in the plantation system for example (Figure 3), but can also lead to large GHG fluxes. Based on the rates of N applied to plantations and cropping systems reviewed here (36 – 195 kgN ha^{-1} y^{-1}), the additional GHG emission associated with N fertilizer manufacturing would be between 31 and 291 kg CO_{2eq} ha^{-1} (DOE 2000, West and Marland 2001). Based on the range of P applications analyzed here (8 – 112 kgP ha^{-1} y^{-1}), the additional GHG flux associated with P fertilizer manufacturing would be between 5 and 66 kg CO_{2eq} ha^{-1} (West and Marland 2001). Over a 60-year period, the combined application of N and P could result in an emission that is up to 14 Mg CO_{2eq} ha^{-1} greater than a management system with no input requirements (i.e. partial harvest). This GHG emission would be in addition to the terrestrial C fluxes we have described (e.g. Figures 3, 5) and reported in table 2. This estimate does not include emissions of N_2O that would occur at the time of fertilizer application, another significant source of GHG in managed landscapes.

In addition to C sequestration and GHG mitigation, environmental sustainability also depends on maintaining or enhancing biodiversity, ecosystem function, and water quality. Low intensity partial harvests, at a site-level or landscape-level, by definition allow the retention of aboveground biomass (e.g. 83% biomass remains standing in a 17% harvest). Therefore, properly designed harvest regimes may maintain the inherent diversity of forest plant communities that mediate biogeochemical cycling and provide habitat for vertebrate and invertebrate wildlife of multiple trophic levels. Nationwide, BMPs often invoke low intensity partial harvests rather than intensive plantations or even-age management at the landscape level to accomplish environmental benefits, primarily maintenance of water quality (Manomet Center for Conservation Sciences, 2010). However, landscape-level patch cutting on a small percentage of land while maintaining a mature forest across the majority of a landscape may be sustainable because this practice limits the number of entry points for machinery that can lead to increased soil disturbance and incur additional costs. Such management requires long-term planning if the goal is to maintain a continuous biomass supply.

There is much uncertainty about the economic sustainability of biomass harvesting from forests. Based on the expected value of cellulosic biofuel feedstocks and known costs of harvesting, we estimated the relative profitability of different timbering practices. The cost of harvesting sawlogs (> 36 cm diameter) is actually lower than the cost of harvesting pulpwood (16 – 23 cm diameter) (Kluender et al. 1998). These sizes correspond to tree age, and partially harvested forests (at a site-level or landscape-level) maintain older trees in larger size classes than trees grown in a short-rotation system (Schuler 2004). If we assume that the value of biomass harvested for fuel is $50 per ton (Khanna et al. 2011), then the profitability on a tonnage basis is greater for low-intensity timbering practices than it is for more intensive plantation management (Figure 6).

Since long-term economic sustainability depends on the biological potential of a managed forest or plantation system, it is important to weigh short-term economic gains against both the biological and economic potential of a forest in the long-term. To do this, economic analyses should distinguish total standing biomass from incremental biomass changes in a forest to reconcile short-term goals with long-term sustainability. Even though a lower amount of biomass per unit area is harvested in low-intensity partial harvests than from clear-cut plantations, the sustainability of production and the value per unit product are greater than high-intensity timbering (Figure 6). The harvest of many small diameter stems is more expensive per unit mass than the harvest of larger stems that yield the same biomass in fewer stems (Kluender et al. 1998). If one assumes a landscape level approach to management, small areas of the landscape might be harvested intensively but large-diameter trees can be cultivated by staggering the location and increasing the interval of harvest at a single location to 80+ years.

Increasing interest in bioenergy is expanding markets for forest materials that have historically had little commercial value, such as small-diameter trees and logging residues (Malmsheimer et al. 2008a, Perlack et al. 2005, Janowiak and Webster 2010). Some of the forest-derived material that could be used for bioenergy already is being extracted from the forest (e.g. living or dead trees removed for fuel reduction or forest health); bioenergetic utilization of this feedstock is limited primarily by transportation costs and processing infrastructure (Perlack et al. 2005). To maintain ecological integrity and ensure sustainability in eastern forests, some proportion of the available biomass in any given stand should remain on site, and this residual material should consist of multiple biomass categories (e.g. large dead wood, small-diameter trees, logging residues). However, precise quantities are mostly unknown and are likely to be highly site-specific (Janowiak and Webster 2010, Evans et al. 2010). Thus we recommend careful consideration of the tradeoffs between economic benefits and local ecology when managing residues.

The 176 Tg y^{-1} of biomass that could be produced relatively sustainably from woody feedstocks in the eastern US is enough to generate 16 billion gallons of ethanol annually. This is equivalent to 4% of liquid fuel consumption in the US in 2009 (EIA 2010). The degree to which energy security objectives can be met by harvesting wood resources in the eastern US depends on the amount of land that is available to provide biomass. Abandoned lands in the east total anywhere from 10.8 to 20.4 Mha depending on the degree to which abandonment of crops was offset by transitions to pasture or vice versa. For each scenario that was discussed here, we can only roughly estimate the potential biomass production from abandoned lands.

Payback times

A payback time is defined as the time it takes to recuperate a lost pool of C plus the loss in the continued stimulation of C sequestration that may have occurred by displacing the baseline condition (Fargione et al. 2008, Anderson-Teixeira and DeLucia et al. 2010). If a new management practice is to be introduced for biomass production, then the initial conditions of forestlands must be considered. The initial conditions define the trajectory of C storage and allow for a more accurate estimate of payback times. All of the scenarios modeled in the results were analyzed without accounting for differences in land use practices prior to agricultural abandonment. The exception to this is the partial harvesting scenario, which assumes a mature closed-canopy forest prior to time zero.

Payback times for an initial disturbance or land use change are handled differently in different disciplines (Searchinger et al. 2008, Davis et al. 2009). One reason for disagreement about the method for calculating payback times associated with bioenergy agriculture is that the conversion efficiency of the bioenergy products (energy per unit C) are not equal to the conversion efficiency of the fossil fuel technology that is being replaced. Displacement of fossil fuels can reduce or eliminate payback times (Farrell et al. 2006). With a displacement of 4% of transportation fuels in the US, the payback would be reduced by 25 Tg C annually (emissions that would no longer be released from fossil fuels). Among the harvesting practices reviewed in this study, pine plantations are the most likely to result in C emissions. With pine plantations on abandoned lands in the southeast included as a source of biomass in the eastern US, we estimated that C would be emitted to the atmosphere at a rate of 1.7 Tg of C y^{-1}. Although we conclude this is unsustainable relative to alternative practices, it should be noted that emissions from intensive forest management for biomass are an order of magnitude less than the emissions currently produced from fossil fuel use.

Relevance to Life-cycle analysis

Our analysis describes only the terrestrial fluxes that would be inputs to a life-cycle analysis of bioenergy production from wood resources. There are many other components that ultimately must be considered when evaluating the production chain associated with each scenario (Davis et al. 2009). Upstream of resource production, one would consider land use change, machinery, land preparation and fertilizer and equipment manufacturing. Downstream, one must consider co-products, fuel conversion processes, transportation, distribution, and infrastructure costs. The focus of this study was limited to terrestrial ecosystem fluxes of GHG.

Conclusion

To optimize the production potential of feedstock sources, there is a choice between management intensification and extensification (Davis et al. 2011). In the case of biomass harvests from forestlands in the eastern US, intensification through site-level plantation management or short-rotation woody cropping reduces the land footprint for a given amount of resource produced, but increases the input requirements and environmental cost. More extensive management is required to produce the same amount of biomass through partial harvests or residue collection, increasing the land footprint for resource production, but reducing inputs and environmental costs. Ultimately, we need feedstock solutions that optimize biomass production, reduce inputs, and lower environmental and economic risks. Our analysis suggests that ~176 Tg of wood biomass could be harvested from eastern US forestlands without diverting current wood products, damaging habitat, or reducing terrestrial C sinks.

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Author contributions

Davis, Dietze, and Long conceived of the project, conducted the research, and wrote the paper. Davis conducted the literature review and the modeling analysis for scenarios 1 and 2. Wang and Dietze completed the literature review and modeling analysis for scenario 3. Youngs, Potts and Ramage completed the literature review and analysis of scenario 4. Loarie and Field completed the mapping and analysis of abandoned lands. DeLucia, Hamburg, and Parton developed ideas for discussion and contributed to writing.

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Table 1. Eastern forest mill and urban residues[a] (1000 dry Mg y^{-1}) (USDA Forest Service, 2007).

State	Forest Residues	Primary Mill Residues		Secondary Mill Residues	Urban Residues	Total
		Total	Unused			
Northeast Region						
Connecticut	78	75	0	24	376	553
Delaware	51	14	0	8	85	158
District of Columbia	0	0	0	0	56	56
Maine	2,890	421	35	15	133	3459
Maryland	263	113	0	33	624	1033
Massachusetts	89	113	0	52	687	941
New Hampshire	986	925	19	18	126	2055
New Jersey	29	17	0	58	894	998
New York	1,111	1,063	24	119	2,041	4334
Pennsylvania	1,679	1,358	144	127	1,238	4402
Rhode Island	8	21	0	6	109	144
Vermont	496	103	0	9	65	673
West Virginia	1,347	807	114	15	184	2353
Regional Total	**9,027**	**5,030**	**336**	**484**	**6,618**	**21,159**
Percent of Total US	**16%**	**7%**	**21%**	**19%**	**21%**	**13%**
Great Lakes Region						
Illinois*	664	233	14	96	1,337	2330
Indiana*	863	574	26	71	715	2223
Michigan	1,275	1,314	41	86	1,196	3871
Minnesota	2,242	985	65	59	496	3782
Missouri*	1,840	1,036	130	69	613	3558
Ohio	796	786	18	124	1,272	2978
Wisconsin	2,011	1,621	30	69	548	4249
Regional Total	**9,691**	**6,549**	**324**	**574**	**6,177**	**22,991**
Percent of Total US	**17%**	**8%**	**20%**	**22%**	**20%**	**14%**
Southeast Region						
Alabama	2,555	5,857	10	57	483	8,952
Arkansas	2,874	3,623	131	32	314	6,843
Florida	1,778	1,901	4	130	1,678	5,487
Georgia	3,556	7,231	66	97	924	11,808
Kentucky	2,055	1,433	77	52	454	3,994
Louisiana	3,384	3,577	14	33	474	7,468
Mississippi	3,825	4,548	79	33	307	8,713
North Carolina	2,995	3,900	14	115	833	7,843
South Carolina	1,733	2,468	9	38	467	4,706
Tennessee	1,319	1,557	153	75	614	3,565
Virginia	2,403	2,147	66	62	813	5,425
Regional Total	**28,477**	**38,242**	**623**	**724**	**7,361**	**74,804**
Percent of Total US	**50%**	**50%**	**39%**	**28%**	**24%**	**44%**
Total Eastern US	**47,195**	**49,821**	**1,283**	**1,782**	**20,156**	**118,954**
Total US	**56,612**	**77,125**	**1,606**	**2,615**	**30,902**	**168,860**
Percent of Total	**83%**	**65%**	**80%**	**68%**	**65%**	**70%**

*Not included ot only partially included in the eastern forest biome defined by WWF and delineated on the map in figure 7.

Table 2. Estimates of land and potential production of woody biomass for bioenergy

	Great Lakes	Northeast	Southeast		Eastern US Total
Unmanaged and unreserved forestland* (ha)	383,000	323,000	1,281,000		1,987,000
Potential biomass from partial harvest annually** (Mg ha^{-1} y^{-1})	**434,067**	**366,067**	**1,451,800**		**2,251,933**
Abandoned cropland (ha)	3,830,000	3,100,000	8,810,000		15,740,000
Abandoned pasture (ha)	110,000	740,000	20,000		870,000
Total abandoned agricultural land (ha)	3,940,000	3,840,000	8,830,000		16,610,000
Regional harvesting practice likely on abandoned land	Short Rotation Woody	Partial harvest	Pine plantation		
Establishment time (y)	8	80	12 to 20		
Biomass available annually after establishment (Mg y^{-1})	8.15	1.13	12.40		
Total potential biomass cultivated on abandoned agricultural lands (Mg y^{-1})	**32,111,000**	**4,352,000**	109,492,000		145,955,000
Total potential biomass with only partial plantation management*** (Mg y^{-1})				**18,613,640**	**55,076,640**
Carbon sequestration rate**** (Mg C ha^{-1} y^{-1})	0.0144	0.542	-0.554		0.0024
Total Carbon sequestered (Mg C y^{-1})	264,322	2,256,346	-4,197,518		-1,676,850
Total Carbon sequestered with only partial plantation management (Mg C y^{-1})				5,480,162	8,000,830
Residues (Mg)	**22,991,000**	**21,159,000**	**74,804,000**		**118,954,000**
Total potential biomass available annually***** (Mg)	55,536,067	25,877,067	94,869,440		176,282,573
Liquid fuel equivalent (billion gallons ethanol)	5.11	2.38	8.73		16.22
Power from combustion equivalent (GWh)	103,852	48,390	177,406		329,648

*Based on US Forest Service 2007
**Calculated based on partial harvest biomass estimates reviewed here that are multiplied by the amount of unmanaged and unreserved forestland
***Partial plantation management assumes that at any given time only 17% of the available abandoned lands are managed as plantations and harvested after 15 years
****Based on literature reviewed in this paper
*****Sum of numbers highlighted with bold text in each region

Figure Legends

Figure 1. Simulated wood production (a) and net C storage (b) of a ~100 y old mixed hardwood forest with partial harvests every 15 years at varied intensities: 10% removal (blue), 17% removal (red), 34% removal (purple), and 51% removal (orange).

Figure 2. Annual growth response of loblolly pine plantation to water inputs (a), nitrogen fertilizer (b), and phosphorus fertilizer (c). P-values describe main effects from the treatment shown in each panel from a full factorial 3-way ANOVA where the interactive effects of water x phosphorus and nitrogen x phosphorus were also significant ($p<0.05$). Dotted line indicates no significant correlation. Solid lines indicate a significant correlation ($p<0.05$).

Figure 3. Simulated wood production (a) and C storage (b) in an abandoned loblolly pine plantation (no harvest- solid line) and a plantation harvested and replanted at 12 y intervals (dashed line). The dotted line indicates C sequestration in soil only, and shaded dashed lines represent the potential production (a) and C storage (b) if fertilizer applications were optimized.

Figure 4. Yield responses of short-rotation poplar (a) and willow (b) to fertilization (upper) and precipitation (lower).

Figure 5. Simulated carbon storage in short-rotation poplar harvested at 8-year intervals (a) and 4-year intervals (b) in Mondovi, WI.

Figure 6. Mean biomass harvested with different managements (a) and estimated profit per Mg biomass with an assumed selling price of \$50 Mg^{-1} (according to Khanna et al. 2011) (b) in different forest management scenarios.

Figure 7. Maximum estimates of abandoned agricultural land in the US that is not currently in forest or urban development, increasing from red to blue (adapted from Campbell et al. 2008). The eastern forest biome that was analyzed in this study is outlined in black.

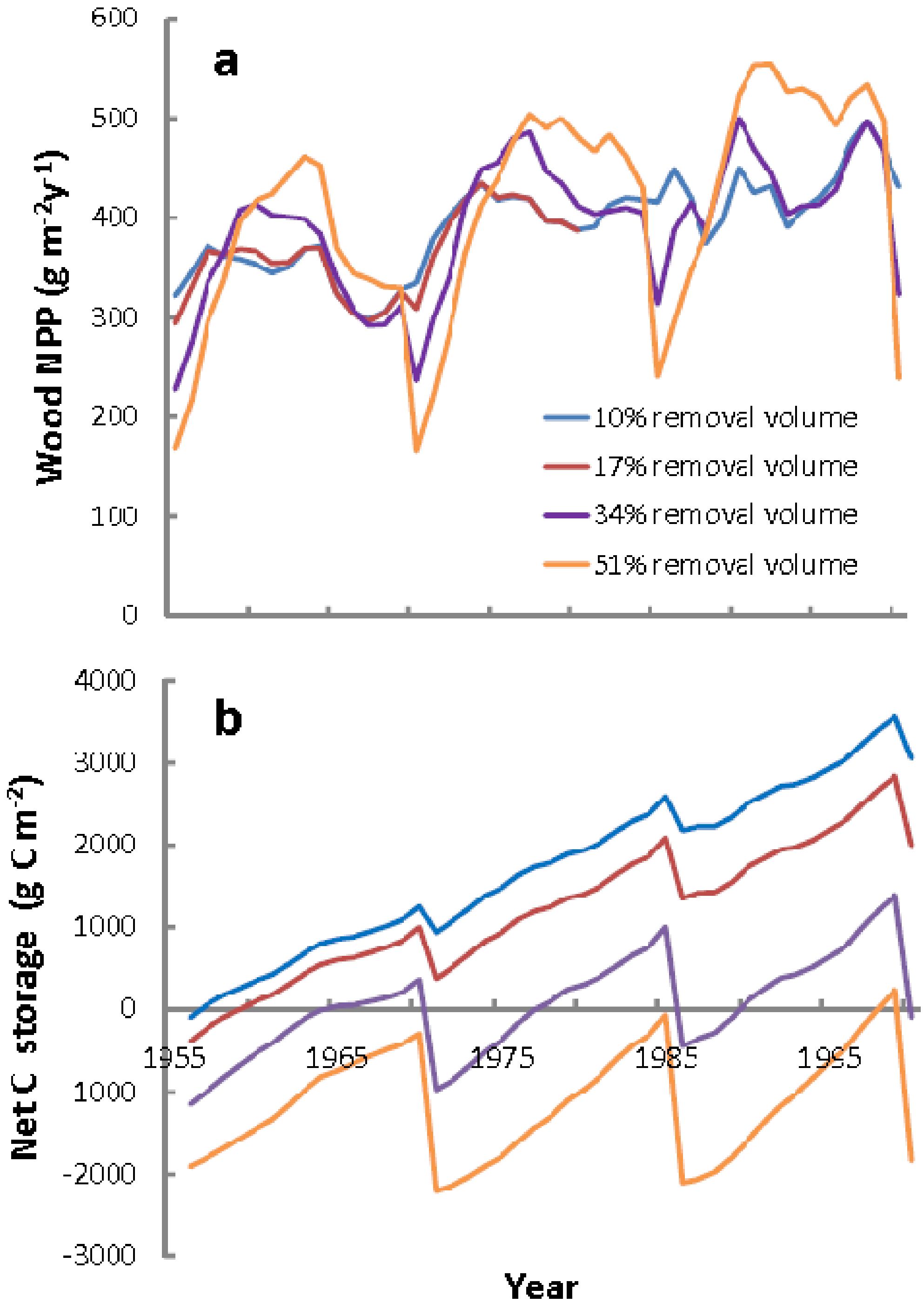
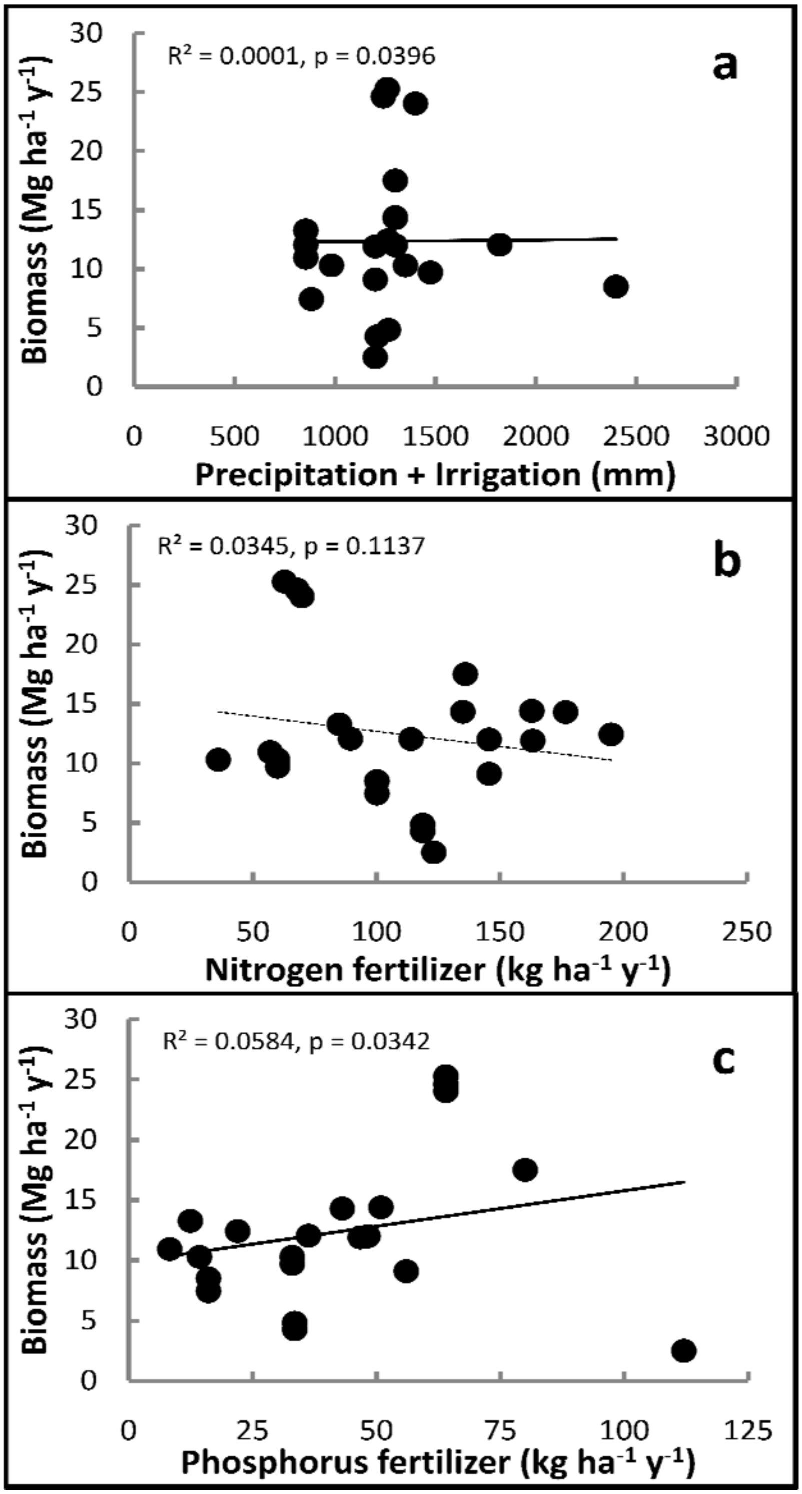
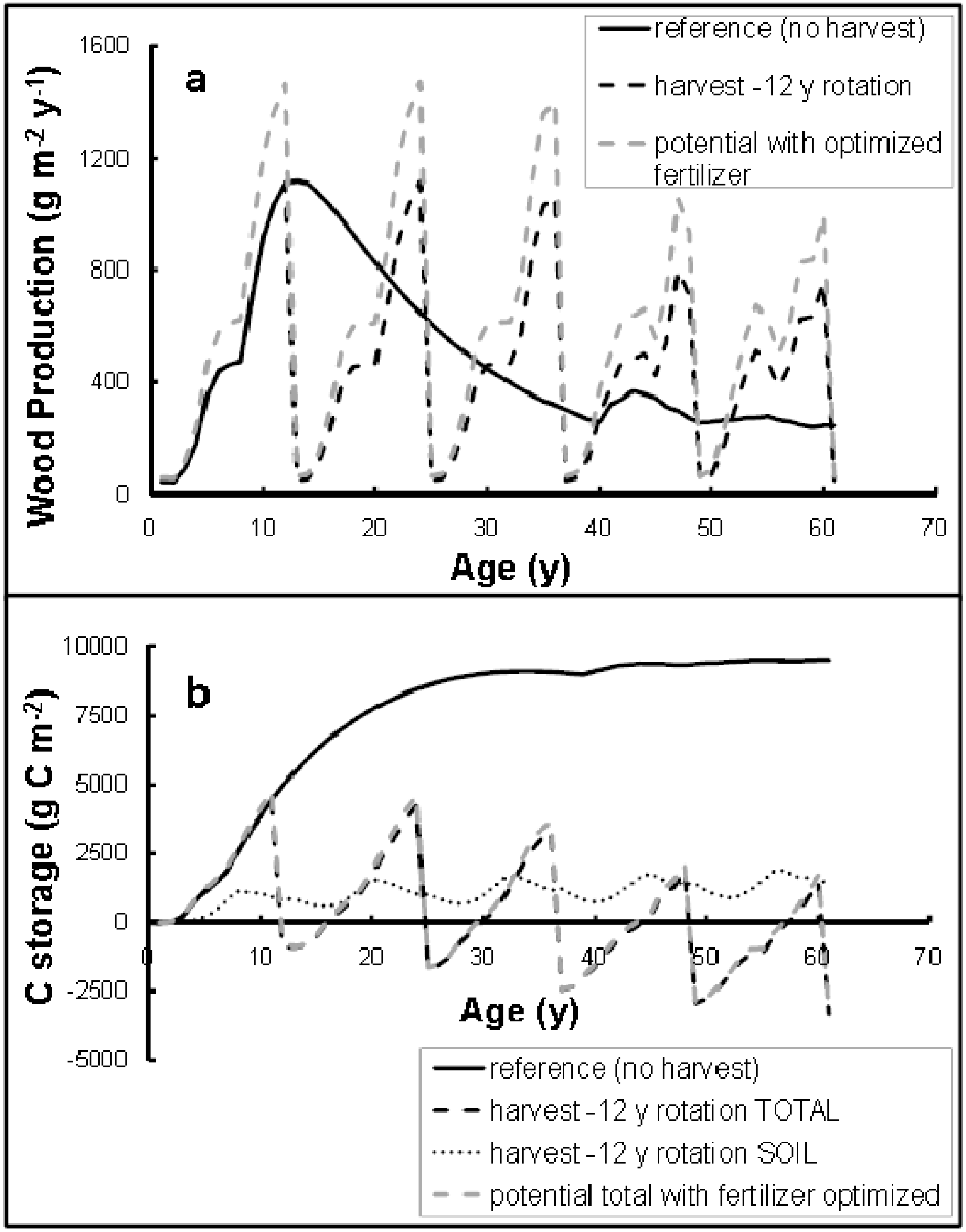

a
b
Wood NPP (g m-2y-1)
Net C storage (g C m-2)
10% removal volume
17% removal volume
34% removal volume
51% removal volume
600
500
400
300
200
100
0
4000
3000
2000
1000
0
1955
1965
1975
1985
1995
-1000
-2000
-3000
Year

Figure 1



a
R² = 0.0001, p = 0.0396
Biomass (Mg ha-1 y-1)
30
25
20
15
10
5
0
0
500
1000
1500
2000
2500
3000
Precipitation + Irrigation (mm)
b
R² = 0.0345, p = 0.1137
Biomass (Mg ha-1 y-1)
30
25
20
15
10
5
0
0
50
100
150
200
250
Nitrogen fertilizer (kg ha-1 y-1)
c
R² = 0.0584, p = 0.0342
Biomass (Mg ha-1 y-1)
30
25
20
15
10
5
0
0
25
50
75
100
125
Phosphorus fertilizer (kg ha-1 y-1)

Figure 2



a
Wood Production (g m-2 y-1)
Age (y)
reference (no harvest)
harvest -12 y rotation
potential with optimized fertilizer
b
C storage (g C m-2)
Age (y)
reference (no harvest)
harvest -12 y rotation TOTAL
harvest -12 y rotation SOIL
potential total with fertilizer optimized

Figure 3

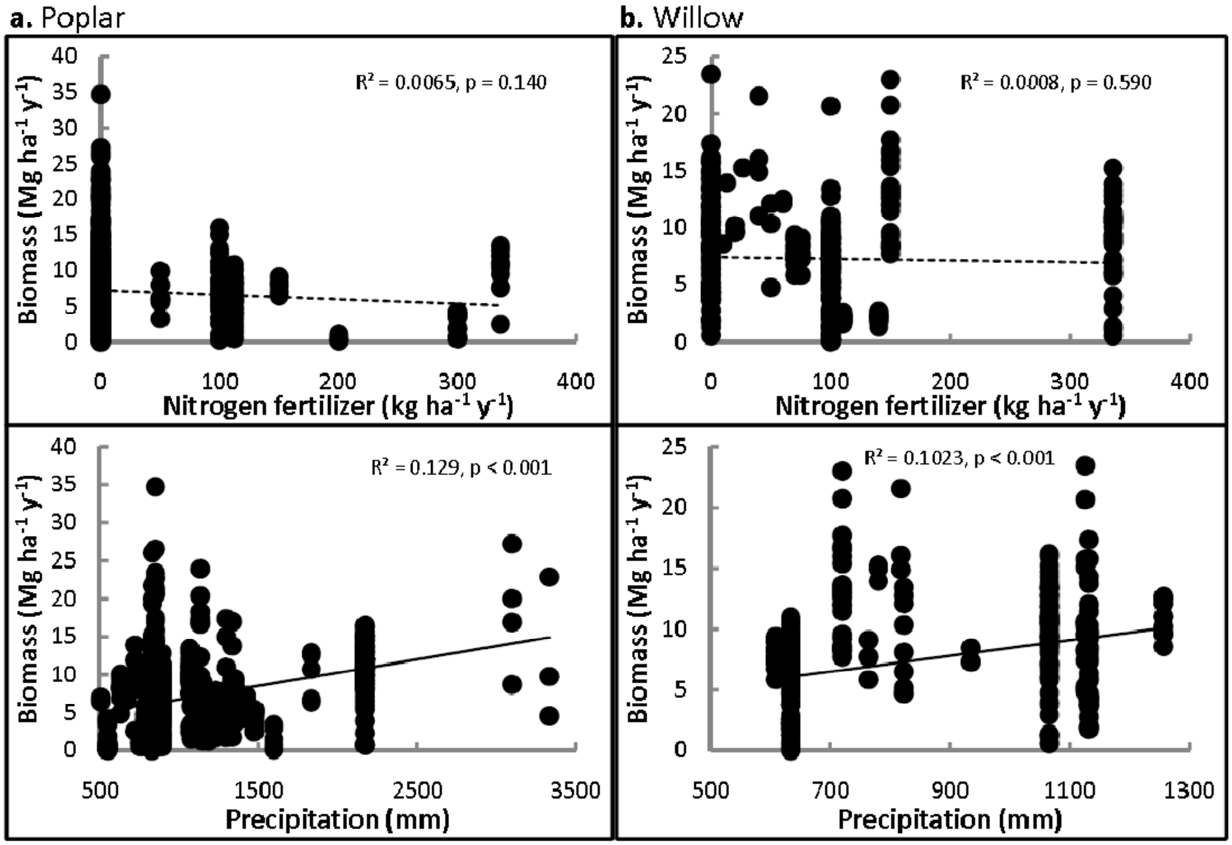

a. Poplar
b. Willow
R² = 0.0065, p = 0.140
R² = 0.0008, p = 0.590
R² = 0.129, p < 0.001
R² = 0.1023, p < 0.001
Biomass (Mg ha-1 y-1)
Nitrogen fertilizer (kg ha-1 y-1)
Precipitation (mm)

Figure 4

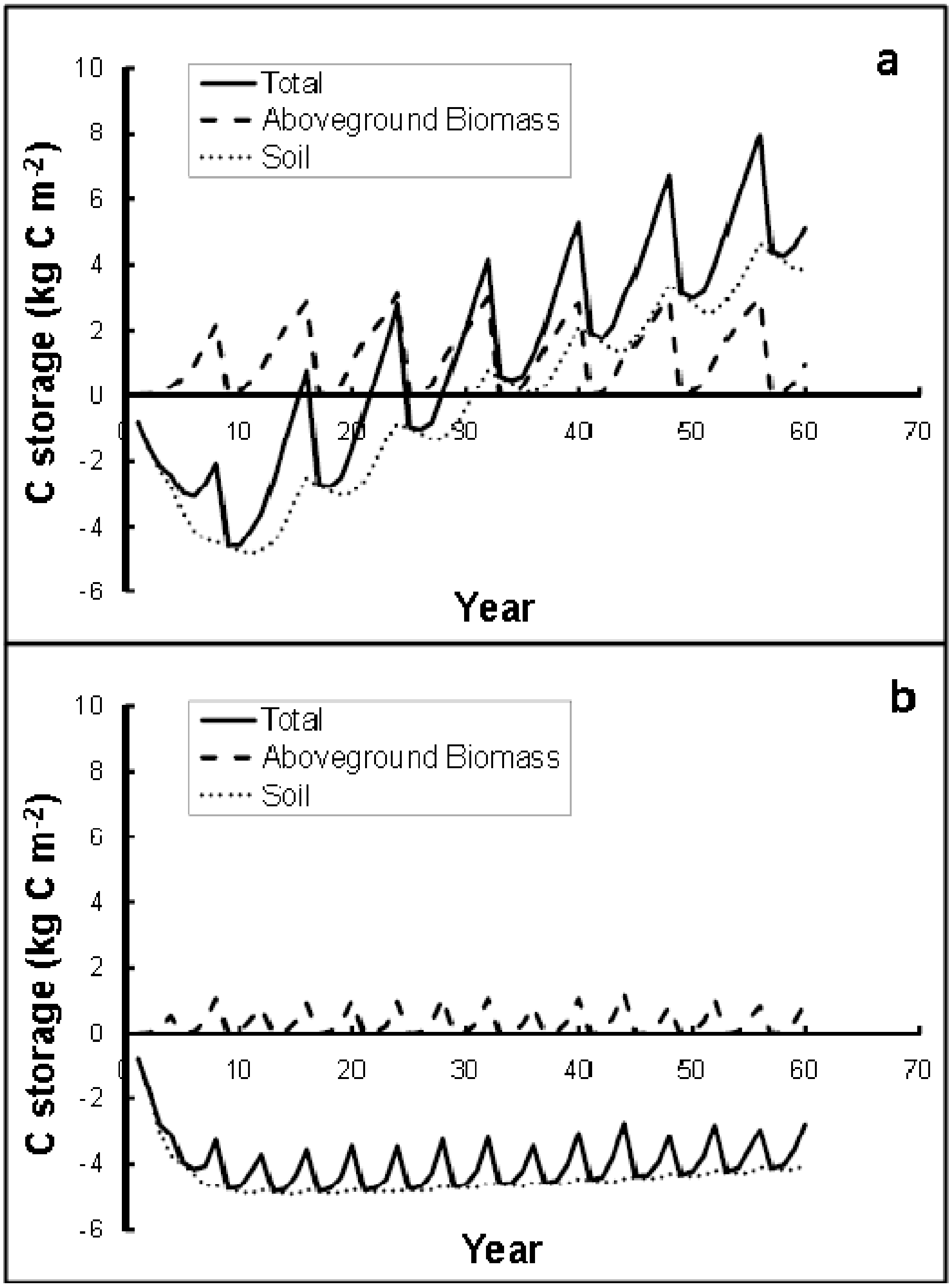


Figure 5

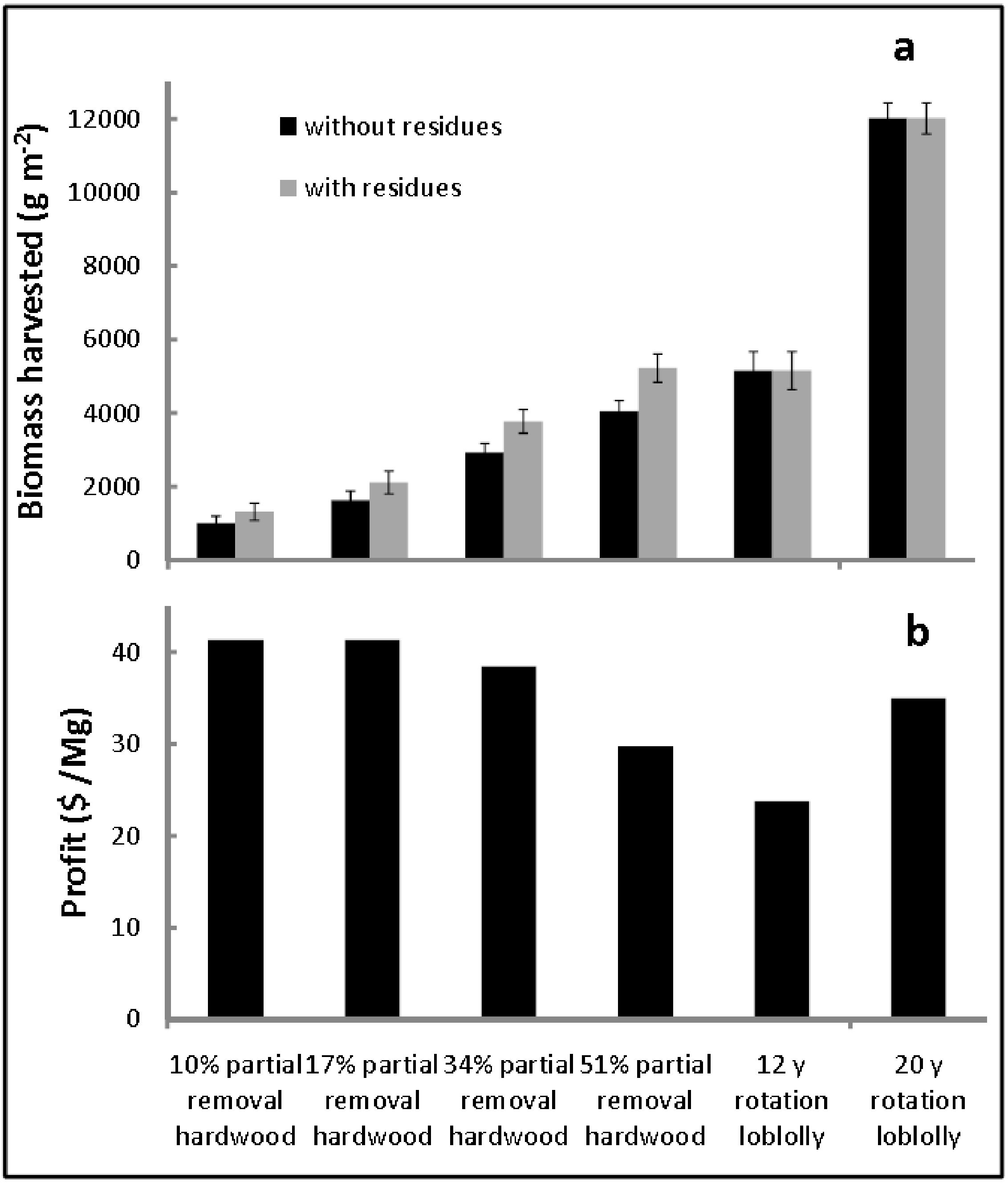

a
b
Biomass harvested (g m-2)
12000
10000
8000
6000
4000
2000
0
without residues
with residues
Profit ($ /Mg)
40
30
20
10
0
10% partial removal hardwood
17% partial removal hardwood
34% partial removal hardwood
51% partial removal hardwood
12 y rotation loblolly
20 y rotation loblolly

Figure 6

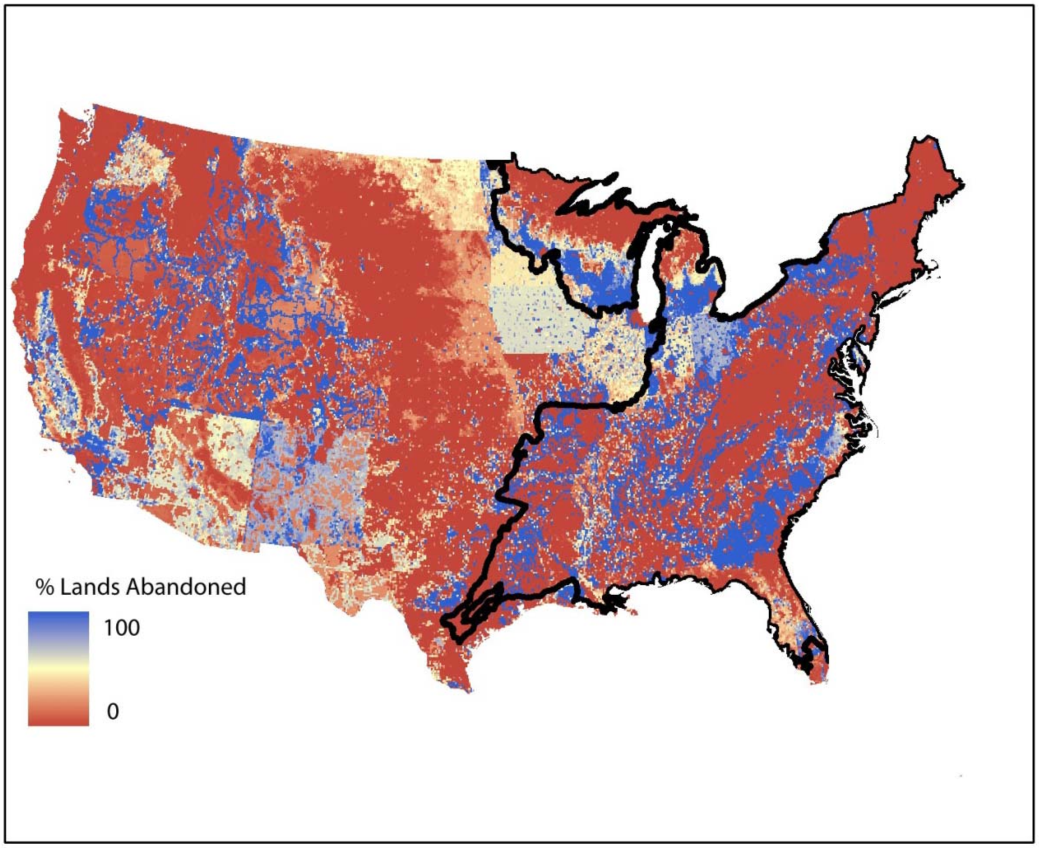


Figure 7