Modeling Biofuel Production in Southern Pine Forests: The Effects on Soil Properties

By

Brittany L. Oakes

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Introduction

It is no longer a debate that the anthropogenic combustion of fossil fuels is increasing atmospheric CO_2, which was recorded at 393 ppm (parts per million) for the month of January in 2012 (Tans and Keeling, 2012). According to many climate professionals, scientists, and developing national governments, CO_2 in our atmosphere needs to be below 350 ppm in order to impede devastating impacts from climate change (IPCC, 2007; Hansen et al., 2008; Rockström et al., 2009). For over a decade, the United States has funded research and development in alternative, renewable energy sources that are low in carbon emissions to ultimately reduce our nation's carbon footprint.

From consuming energy alone in 2009, the United States ranked second as a carbon emitter at 5,425 million metric tons annually; China was the leader at 7,706 million metric tons and India placed third at 1,591 million metric tons (EIA, 2010). Yet in 2009, the U.S. consumed more electricity than both China and India and was the leading importer of electricity (EIA, 2010). Incorporating more domestic sources of renewable energy can simultaneously alleviate two issues: mitigating climate change catastrophes and significantly reduce our dependence on foreign markets for electricity and other forms of energy. Additionally, evidence of dwindling international oil reserves (i.e., the main energy source used to generate electricity) further support that we need to act urgently and decisively to develop alternatives that are sustainable, clean and affordable renewable energy sources to enhance our future energy security (Owen et al., 2010; EIA, 2011).

Pressures to develop alternative energy sources with low carbon emissions have steered significant attention to increasing cellulosic biofuel production from current domestic resources. Contemporary projections estimate that by 2035 electricity generated by renewables will account for 26% of the total U.S. generation (EIA, 2011). More specifically, domestic energy obtained from liquid biofuels is expected to increase from 5% in 2009 to 15% in 2035, with particular attention paid to the growth of cellulosic biofuels (EIA, 2011). Considering that the transportation sector accounted for nearly a third (29%) of total U.S. energy consumption in 2009, liquid cellulosic biofuel is the leading candidate as a renewable energy source in that it is currently the only available transportation liquid substitute (EIA, 2011). The future of biofuels may be promising in some sectors, however incorporating multiple sources of alternative and renewable energies will be necessary to replace petroleum completely.

Forest biomass doubles as an alternative, renewable source of energy and as a mechanism to sequester and store carbon in soil and vegetation pools. Biomass is characterized as 'carbon-neutral' in the sense that the amount of CO_2 released during combustion is equivalent to the amount removed from the atmosphere during photosynthesis (Johnsen et al., 2001a). There is currently 504 million acres of U.S. land identified as timberland that serves as the primary source of all current forest-derived bioenergy consumption; 72% of this national timberland is located along the eastern United States (Smith et al., 2009). In most areas, the infrastructure and technology to harvest wood already exists making forest biofuels more attractive than other developing renewable sources.

Extracting more energy from cellulosic biofuels will likely lead to land use changes and intensified harvesting techniques. Timber companies may now have more of an incentive to harvest more trees in a given area and to collect more logging residue that would normally be left on site. Additional energy could be harnessed without expanding the land area dedicated to timber management by increasing the frequency of conventional techniques, and by harvesting waste products, specifically logging residue. In 2006, 15 billion cubic feet of timber was harvested for industrial products and fuel, but an additional 4.5 billion cubic feet of unused logging residue was left unused (Smith et al., 2009).

Logging residue is commonly defined as the unused portion of timber (i.e., branches, bark, needles) that is killed and left on the forest floor after harvesting. Curtis et al. (2003) estimated that up to 15% of each individual tree is left behind as logging residue following a timber harvest. There are several economic advantages and disadvantages in collecting this logging residue for increased bioenergy production. Transitioning to a primarily biobased economy will augment growth in the forest equipment manufacturing, construction and biotechnology industries by creating a market for nonmerchantable wood, while also ameliorating rural economies and creating local jobs. Additionally, current estimates suggest that harvesting logging residues could save timber companies up to \$200-250 ha^{-1} in site preparation costs, such as managed thinning and fertilizer applications (Gan and Smith, 2007). On the other hand, harvesting, collecting, processing, and transporting residues presents timber companies with an additional cost and is not viewed as economically profitable or attractive, especially when producing or importing petroleum to generate electricity is significantly less expensive in comparison (SSEB, 2006). The disadvantages stemming from financial burdens could be reduced, or even eliminated, if future biomass facilities were established in areas with high forest biomass density, thus reducing transportation costs and fuel.

Concerns also exist among the scientific community regarding the sustainability of collecting logging residues, or harvesting the whole tree, and the overall impacts this management practice may have on site productivity and soil properties. Forest biodiversity is also another issue of concern (Rosenvald and Lõhmus, 2008). Several studies have evaluated effects on subsequent tree regeneration (Proe and Dutch, 1994; Dutch 1995), total ecosystem nutrient capital (Barrett et al., 2009; Devine et al., 2012), N leaching and soil C storage (Nave et al., 2009; Devine et al., 2012), and soil compaction, siltation, and erosion affects on local water quality and fish populations (Neal et al., 1992; Nisbet et al., 1997). When left on site, logging residue functions as a protective cover on the forest soil; the removal of this layer exposes the soil to the elements and may increase erosion. Some observations describe a short-term increase in soil C and N following harvest regimes that leave logging residue (i.e., conventional sawlog) to decompose on site (Harvey, 1982; Knoepp and Swank, 1997; Hart, 1999). However, other research has found that whole-tree harvesting removed three times as much C and N from the soil than in conventional sawlog (Phillips and Van Lear, 1984; Johnson et al., 1982; Alban et al., 1978), while concentrations of N, P, and K decreased in forest vegetation up to three or four times greater from whole-tree harvest techniques (Walmsley et al., 2008). In addition, tree regrowth data from various sites located throughout the U.S. revealed that stands subjected to conventional sawlog treatments were greater in biomass volume following harvest than in whole-tree harvest experiments (Mann et al., 1988).

Loblolly pine plantations in the southeastern United States are a significant source of forest-based products, so it is not surpising that logging residue generated from these forests are a particularly attractive source of bioenergy (Scott and Dean, 2006; Fox et al., 2007). Although, an additional 16 to 22% of biomass can be obtained by implementing whole-tree harvest regimes in southern pine plantations, the adverse effects of removing residue are not completely understood and necessitate further analysis (Phillips and Van Lear, 1984). Phillips and Van Lear (1984) found that whole-tree harvests doubled the amount of C and N removed from the soil than in conventional harvests, while Pye and Vitousek (1985) found an increase in soil erosion. On the other hand, some studies have reported that there was no measureable effects on soil carbon and nitrogen supply from intensifying harvest in pine stands (Carter et al., 2002; Westbrook et al., 2007; Eisenbies et al., 2009); however, nearly all of these conclusions were based on field experiments that analyzed short-term ecosystem data and observations. It is extremely important that we analyze and attempt to understand the long-term effects from whole-tree harvesting on loblolly pine ecosystems. Ultimately, it needs to be determined whether this intensified timber management practice is sustainable, or if it leads to the degradation of forest productivity over a longer period. Additionally, understanding the long-term effects is especially important if this potential source of bioenergy begins to be widely implemented in the southern U.S.

Field investigations analyzing the long-term effects of harvest intensity on loblolly pine stands take time and money and could be too slow to warn policy makers of any adverse effects. Rather, computer models can be used to simulate different harvest regimes over short and long periods, and analyze the effects of whole-tree harvest on components of the ecosystem (i.e., soil pool, forest floor, vegetation, etc.) (Johnsen et al., 2001b; Peng et al. 2002). Using an ecosystem model called DailyDAYCENT, I evaluated the C and N dynamics throughout the ecosystem in response to conventional sawlog and whole-tree harvest practices in Duke Forest, North Carolina. I hypothesized that C and N in the soil, forest floor, and vegetation components would decline, leading to a reduction in the amount of C and N in the entire forest systeml. I also theorized that differences between the two harvesting regimes would become more prevalent with more crop rotations and lengthened time, suggesting that this practice may lead to degraded forest productivity and is unsustainable.

Methods and Materials

Model Description

DailyDAYCENT is a daily time step version of the biogeochemical model CENTURY developed by Parton et al. (1994). DailyDAYCENT simulates fluxes of carbon, nitrogen, phosphorus, and sulfur between the atmosphere, vegetation, and soil for a variety of ecosystem types (Del Grosso et al., 2001; Parton et al., 1998). C and N dynamics among the different pools are dependent on pool size, material lignin content, and temperature and abiotic water effects. Plant production is a function of nutrient and water availability, and temperature, whereas available nutrient stock is controlled by decomposing soil organic matter (SOM), substrate availability and quality (lignin content, C and N ratio), and temperature and water stress (Del Grosso et al., 2006). Fundamental sub-models include soil water and temperature dynamics specific to soil layer, plant productivity and allocation of net primary productivity (NPP), decomposition of plant litter and SOM, nutrient mineralization, and trace gas fluxes. The allocation of NPP to particular vegetative components depends on vegetation type, phenology, and water/nutrient stress. DailyDAYCENT is capable of simulating ecosystem disturbances and events such as fire, forest harvest, irrigation, cultivation, grazing, and organic matter or fertilizer additions.

Site Description

The six divisions of Duke Forest span 7,060 acres (2,860 ha) in Durham, Orange, and Alamance Counties of North Carolina. Since 1931, this forest has been managed and maintained by Duke University, providing research, teaching, and recreational opportunities (Parashkevov, 2008). Meticulous data recording began during the 1930s and 1940s and provide a long-term scientific record that exemplifies forest ecosystem changes. In this study, we focus on the Blackwood Division (Orange County) which has remained relatively undisturbed since 1983 when the whole division was clear-cut and burned, and planted with loblolly pine (*Pinus taeda L.*) (Parashkevov, 2008). This division is characterized by rolling terrain (<5% slopes) and low-fertility Hapludalf soils in the Enon Series (clayey loam and fine-textured clay), typical of upland regions in the southeastern United States. This site experiences a moderate climate with precipitation usually well distributed throughout the year at approximately 44 in. The forest cover is composed of over 100 species of trees and is categorized by four major types: pine, pine-hardwood, upland hardwood, and bottomland hardwood. The most common tree characterizing the Blackwood Division is loblolly pine, followed by shortleaf and Virginia pine (Parashkevov, 2008).

Simulating Harvest Management Strategies

We utilized DailyDAYCENT to simulate five timber management strategies in Duke Forest. Before management strategies were instituted, we ran the model using pre-existing schedule files (i.e., spin.sch, base.sch, and amb.sch) as extensions that simulate historical events from 1750 to 1983 in Duke Forest; in the year 1983, the forest was planted with loblolly pine (Duke FACE Site). This step was necessary to allow all variables to reach values (i.e., concentrations) that accurately reflect the forest ecosystem that existed in 1983. For this experiment, we modified input variables that determine the fraction of timber to be harvested (only altered for managed thinning) and quantity of logging residue removed from the site (Table 1). In the trem.100 file – a key file defining particular treatments such as timber cuts and forest fires – we altered the input parameters remf(1-3) and retf(1-3). Remf(1-3) describes the fraction of live leaves, fine branches, and large wood harvested and removed from the forest system, whereas retf(1-3) delineates the fraction of C, N, P, and S that is returned to the system in dead leaves, fine branches, and large wood. These input parameters must range from 0 to 1 (0% to 100%), so a higher value simulates an increased percentage of harvested timber for remf(1-3) and a larger fraction of logging residue left to decompose on site for retf(1-3) (Table 1).

Treatment Descriptions

We simulated five distinctive treatments; undisturbed forest (the control), sawlog, whole tree harvest (WTH), sawlog with thinning, and WTH with thinning (Table 1). The uncut forest illustrates dynamics in C and N pools that would occur if managed timber harvesting never occurred and no biomass was removed from the site. Southeastern loblolly plantations commonly clearcut (cut 100% of the trees) when harvesting timber, and is why all four treatments are characterized by 100% harvests (Table 1). The WTH treatment differed from the sawlog simulation in that all dead leaves, fine branches, and large wood residues were harvested and removed from the site (Table 1). We defined this treatment to demonstrate more intense management strategies in southern loblolly pine plantations intended to increase forest biofuel production.

The other two harvesting management treatments simulated pre-treatment thinning half way through a full 35-year crop rotation, followed by either sawlog or WTH at the end of the rotation (Table 1). Several studies suggest that managed thinning reduces species competition and yields higher forest productivity in a shorter time period; the more managed thinning (up to 2 or 3 thins, but no more), the faster the forest will grow (Cunningham et al., 2008). Thinning management values are specific to the sawlog and WTH treatment definitions (Table 1).

All five treatments simulated forest growth from 1983 to 2053 – a total of 70 years. Loblolly pine plantations often rotate the trees every 35 years, which is why we choose tree age to be 35 at harvest and 17 for pre-treatment thinning (Nebeker et al., 1985; TMMC, 2003). Our 143-year simulation encompasses three harvest events – in 2018, 2053, and 2087 plus thinning in appropriate treatments in 2000, 2036, and 2072. For both the 70- and 143-year simulations, all final harvest and pre-treatment thinning events were instituted on day 30 of the month of June.

Evaluation of Model Outputs

For the purpose of this study, we evaluated changes in 13 output variables over time, including cproda, fsysc, fsyse(1), somtc, somte(1), strucc(1), struce(1,1), som1c(1), som2c(1), som1e(1,1), som2e(1,1), metabc(1), and metabe(1,1) (Table 2). The first variable, cproda, was targeted for evaluation considering it directly measures net primary productivity (NPP) of the entire loblolly pine ecosystem (Table 2). The other 12 output variables investigate changes in carbon and nitrogen concentrations, and were grouped to represent four fundamental components of the forest ecosystem: the total forest system, vegetation pool, soil pool, and forest floor. This method allowed us to focus on trends in each ecosystem component, and to observe changes in minerals that are essential for forest productivity. The vegetation pool represents living coarse and fine roots, fine branches, large wood, and leaves (Table 2). By combining the output values of strucc(1), som1c(1), som2c(1), and metabc(1), we were able to analyze total C on the forest floor (Table 2). Likewise, struce(1,1), som1e(1,1), som2e(1,1), and metabe(1,1), calculated total N on the forest floor.

We analyzed all variables during the month of June because this month represents a period of active growth, and so therefore is likely a time of maximum biomass and vegetation nutrient content during the year.

Results

The Undisturbed Forest

For the undisturbed forest simulation, two general trends were evident in the graphical representations, and allowed the variables to be grouped by similar trends. As the undisturbed forest grew, the concentrations of C and N continuously increased and showed little to no sign of stabilizing in the vegetation and forest floor components (Fig. 1-4). Total forest floor C experienced a slight cyclic decrease every 15- 20 years and appeared to be reaching a state of stabilization near the end of the 143-year period (Fig. 3). Total C and N in the soil pool followed a very different pattern, in that they rapidly declined when the forest grew initially, and began to gradually increase around year 2030 (Fig. 5, 6). Additionally, we see that total N in the soil increased more rapidly than soil C when evaluated over a longer period (Fig. 5, 6).

Quantitatively speaking, most C within the ecosystem was allocated to the vegetation and soil pools; with time, C was increasingly allocated to forest vegetation and while it declined in the soil (Table 3). On the other hand, almost all the N was distributed to the soil, but decreased slightly as N increased in the vegetation and forest floor components (Table 3). The difference in NPP between the 70- and 143-year simulations was minute, and thus negligible (Table 4).

WTH vs. Sawlog Management

Total C and N concentrations in the forest vegetation pool dropped sharply after each harvesting event (Fig. 1 & 2). The decline was higher in magnitude in the WTH treatments than the sawlog treatments (Table 5). This slight difference in magnitude was apparent in the soil and forest floor components also. We observed an initial spike in total soil C and N concentrations following sawlog treatments (Fig. 3-6). Following a harvest, both soil and forest floor C and N declined compared to pre-harvest values, and evidently declined the farthest in response to the WTH treatment (Table 5; Fig. 3-6). In general, all forest system components experienced the greatest impacts from the WTH treatment.

The distribution of C and N in the various forest system components changed in response to sawlog and WTH treatments (Table 3). Half of the C in the total system was distributed to the soil pool after both harvesting strategies were implemented (Table 3). Likewise, nearly all of the N (>90%) was allocated to the soil pool (Table 3). Overall, observed differences in the allocation of C and N that correspond to the sawlog and WTH treatments were small.

Pre-treatment Thinning vs. No Thinning

Seeing that managed thinning is a widely used technique in the southeastern U.S., we simulated sawlog and WTH strategies that incorporated pre-treatment thinning half way through a full 35-year crop rotation. All scheduled thinning events had less of an impact on forest system components compared to the full clearcut harvest, and when the full harvest was implemented pre-treatment thinning effects were minimal (Fig. 1-6).

One Harvest vs. Three Consecutive Harvests

The general patterns observed in response to three consecutive harvesting events (i.e., the 143-year simulation) initially mirrored the trends detected from one harvest event (i.e., the 70-year simulation). Soil and vegetation C and N concentrations accrued over the three harvests for both the thinned and not thinned sawlog treatments (Fig. 1-4). This trend is also evident in total forest floor N, but is less apparent in forest floor C (Fig. 3, 4). On the other hand, we observed the opposite trend in all system components in response to the thinned and not thinned WTH treatments. The concentrations that C and N in the soil, vegetation, and forest floor pools reached immediately before harvesting slightly decreased with time and was enhanced with each harvest that followed (Fig. 1-6). For both the sawlog and WTH treatments, the effects of varying harvesting intensity appeared to be additive when analyzed over a longer period with three consecutive harvests.

The differences in final concentrations of C and N between the sawlog and WTH treatments (with thinning) virtually doubled from those detected in the simulation with one harvest event (Table 5). However, the distribution of C and N in the various ecosystem pools was strikingly similar for both harvest management scenarios (Table 3). When compared to the distribution of C and N after a 143-year period of undisturbed forest growth, we see that the fraction of C allocated to the vegetation and soil is affected substantially (Table 3). The percent of C allocated to the vegetation declined by almost half, whereas the soil contained twice as much C than observed in the undisturbed forest (Table 3). This notion is supported by the 8% decline from the sawlog NPP to the WTH treatment's NPP value (Table 4). Overall, we observed that both of the WTH treatments (i.e., with thinning and without thinning) had an additive affect on C and N concentrations in all forest components that caused levels to consistently decrease with each harvest.

Discussion

The quantity and distribution of C and N in the simulated loblolly pine plantation changed in response to conventional sawlog and whole-tree harvest management. As expected, the removal of logging residue with WTH operations resulted in reduced C and N concentrations in the soil, forest floor, and vegetation components in comparison to sawlog strategies. The largest impacts were observed in vegetation and forest floor pools, while changes in soil concentrations were small and essentially negligible. Laiho and others (2003) observed similar results in a different NC loblolly pine plantation: WTH led to slight but significant reductions in forest floor, and vegetation C levels. However, C and N losses in this study were minor in comparison to previous research where WTH either doubled or tripled the amount of nutrients removed from the system (Johnson et al., 1982; Phillips and Van Lear, 1984).

Following the institution of a harvest, vegetation C and N experienced an immediate decline across all harvest regimes, representing the effects of simulating clearcut harvesting when all trees are cut down. Although all above ground vegetative material was removed, the incorporation and rapid decomposition of remaining root systems signaled an initial spike in soil C and N concentrations right after harvests; this trend has been observed in previous research (Powers et al., 2005; Butnor et al., 2006). The magnitude of this spike was larger in sawlog simulations in comparison to WTH, and was evident in forest floor N signals as well. The larger magnitude spike from sawlog harvesting has often been attributed to the incorporation of logging residue nutrients into the soil component (Johnson and Curtis, 2001; Johnson et al., 2002).

The concentrations of C and N in the entire loblolly pine system were lower with the removal of logging residue in WTH practices than with the return of this residue in sawlog strategies. The removal of logging residue – a rich source of essential nutrients – prevented this source of C and N from re-entering the system that conventional techniques returned (Eisenbies et al, 2009). This missing flux of C and N from decomposing residue ultimately degraded and detracted slightly from forest productivity (NPP). Pye and Vitousek (1985) inferred that greater soil losses with whole-tree harvesting compared to conventional regimes on loblolly pine sites may result in degraded forest productivity over the long-term.

The differences in C and N levels between the two simulated harvesting regimes became more prominent and actually doubled with a longer experimental period and more crop rotations (i.e., 70 vs. 143 yrs and 1 vs. 3 final cuts). In fact, the results suggest that leaving logging residue on site augments a slight accumulation of C and N in almost all ecosystem components: soil C and N are the exceptions. This is based on the observed increase in the concentrations preceding harvest from the first, to the second, and finally to the third harvest values. When the whole loblolly pine tree was harvested and the logging residue was no longer contributing to the ecosystem, C and N in the soil diminished with each harvest, revealing an overall additive effect on concentrations. Specifically analyzing soil nutrient processes in TX and LA pine stands, Carter and colleagues (2002) found no measurable difference after two rotations, although, their research contests that later rotations may show larger differences between WTH and sawlog treatments similar to the results presented in this study.

In particular components of the system, especially the vegetation and soil, timber management practices dramatically altered the distribution of C. Consistent with previous research conducted in a loblolly pine plantation in SC, these results show that more than half of the C was found in the vegetation and over a quarter in the soil and forest floor after 143 years of undisturbed forest growth (Johnson et al, 2002). Regardless of the harvesting regime, the distribution of C in the system was affected by timber management and was mostly located in the soil rather than the vegetation following three crop rotations, which makes sense since there is an overall reduction in NPP. Nearly all of the N in the forest ecosystem was distributed to the soil also, regardless of the type of management strategy utilized. The allocation of N changed in the soil and vegetation pools, but to a much lesser degree than C.

Ultimately, the trends observed in this experiment suggest that whole-tree harvesting practices may be sustainable in the long run, since effects on C and N concentrations in various components of the ecosystem were minor. The C and N in the vegetation declined the most from WTH, and is most likely due to the decrease in total nutrient capital and reduced availability of these nutrients for loblolly pine growth and production. Soil N is primarily made available for vegetation uptake through decomposition and microbial processes (i.e., the nitrification of ammonium to nitrites and finally nitrates), which are relatively slow in nature and often determine the rate of tree growth (Schlesinger, 1997). Moreover, these processes also affect the amount of C and N distributed to the vegetation: if tree growth is slowed by soil N availability, then the vegetation will slow down the rate at which C is extracted from the atmosphere and less C and N will be stored in the vegetation. I argue that decreased soil and forest floor N may be limiting vegetationg growth. It is possible that the mobile species of N is not in great abundance and is causing reduced concentrations of C and N in the vegetation. Conversely, Sanchez and colleagues (2006) found that removing logging residue on NC and LA sites reduced P availability and supply, and adverse effects on tree regrowth could be counteracted with the use of fertilizers. Many policy makers and researchers suggest that fertilizer application is a sufficient way in replenishing nutrient stocks and enhancing availability; however, this strategy has its drawbacks and should also be simulated to analyze how effective this practice might actually be (Johnson et al., 2003; Sanchez et al., 2006). Other researchers argue that small nutrient losses in pine plantations can be replaced by annual atmospheric deposition, rather than with the use of fertilizers (Westbrook et al., 2007).

Many scientists argue that site quality is one of the main factors determining the resilience of that site to timber management practices (Carey, 1980; Chapin, 1980; Mroz et al., 1985; Burger, 2002; Sanchez et al., 2006; Scott and Dean, 2006). Already P deficient loblolly pine stands could potentially translate to the long-term degradation of forest productivity (Sanchez et al., 2006). Carey (1980) suggests that sites with acid soils of inherently low fertility are especially sensitive to whole-tree harvesting practices, and could lose the ability to sustain forest productivity in the long-term. Eisenbies and others (2009) concluded that although field experiments show that removing logging residue does not negatively impact forest productivity, short-rotation tree species need to be analyzed more closely over longer periods, especially if there are sites low in quality that are particularly sensitive to this management practice.

Conclusion

Model simulations executed in this experiement strongly suggest that ecosystem effects from WTH techniques are small and potentially negligible, and that biofuel production could be practiced sustainably in the southeastern United States. Although net primary productivity degraded slightly in this experiment, the application of fertilizers is often used to maximize productivity by enhancing tree growth and turnover rates, and could mitigate minor nutrient losses from removing residue. However, the effectiveness of fertilizers may be dependent on local characteristics that define the quality of a specific site. Additionally, fertilizer application is a short-term solution to a potentially long-term problem; they do not prevent soil erosion, and the addition of N or P can negatively affect the surrounding water bodies and municipal drinking supplies if leaching occurs. In this case, future research and modeling needs to integrate fertilization and analyze the effects of applying fertilizers on forest productivity and the surrounding ecosystem before forest biofuel management becomes a widespread practice in the southern U.S. forests.

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Tables and Figures

Table 1

The four treatments used to simulate different harvest intensities by running DailyDAYCENT and manipulating the quantity of trees and logging residue collected during a harvest event.

		Fraction of Live Tree Removed (%): remf (1-3)			Fraction of Debris Left on Site (%): retf(1-3)		
Simulated Harvest Type	**Description**	**leaves: remf(1)**	**fine branches: remf(2)**	**large wood: remf(3)**	**leaves: retf(1)**	**fine branches: retf(2)**	**large wood: retf(3)**
Uncut	undisturbed forest	0	0	0	0	0	0
Sawlog	conventional harvest	100	100	100	100	100	0
Whole tree harvest (WTH)	potential biofuel harvest	100	100	100	0	0	0
Thinning	managed thinning for sawlog harvest	50	50	50	0	0	0
	managed thinning for WTH	50	50	50	0	0	0

Table 2

The DailyDAYCENT output variables utilized to evaluate C and N dynamics in response to varying harvest intensities in five major components of the loblolly pine ecosystem.

Ecosystem Components	DailyDAYCENT Output Variable	Definition
Total Forest System	fsysc	total C in the forest system (i.e., sum of organic matter, trees, dead wood, forest litter) (g/m2)
	fsyse(1)	total N in the forest system (i.e., sum of organic matter, trees, dead wood, forest litter) (g/m2)
Vegetation Pool	frstc	sum of C in the living forest components (g/m2)
	frste(1)	sum of N in the living forest components (g/m2)
Soil Pool	somtc	total C, including belowground structural and metabolic C (g/m2)
	somte(1)	total N, including belowground structural and metabolic N (g/m2)
Forest Floor	strucc(1)	structural C in forest litter on the forest floor surface (g/m2)
	struce(1,1)	structural N in forest litter on the forest floor surface (g/m2)
	som1c(1)	C in the active surface soil organic matter (g/m2)
	som2c(1)	surficial slow pool C organic matter (g/m2)
	som1e(1,1)	N in the active surface soil organic matter (g/m2)
	som2e(1,1)	surficial slow pool N organic matter (g/m2)
	metabc(1)	metabolic C in surficial litter (g/m2)
	metabe(1,1)	metabolic N in surficial litter (g/m2)
Net Primary Productivity (NPP)	cproda	annual accumulator of C production in forest (i.e., NPP) (g/m2/year)

Table 3

The percentage of C and N allocated to each component of the forest system after a 70- and 143-year period of undisturbed new forest growth and disturbed forest growth comparing one and three consecutive harvest events (month of June values are reported).

	Forest Component	% of Total Forest System					
		70 Years			143 Years		
		Uncut	*Sawlog*	*WTH*	*Uncut*	*Sawlog*	*WTH*
C	*Vegetation*	45.58	33.53	32.20	64.16	35.77	32.93
	Soil	40.45	51.82	53.29	25.34	49.30	52.31
	Forest Floor	13.66	13.78	13.66	10.26	14.00	13.91
	Dead Biomass	0.31	0.88	0.86	0.24	0.93	0.85
N	*Vegetation*	4.93	3.47	3.28	9.01	3.74	3.31
	Soil	88.42	91.20	91.69	82.77	90.51	91.49
	Forest Floor	6.60	5.23	4.94	8.14	5.63	5.11
	Dead Biomass	0.06	0.10	0.09	0.09	0.12	0.09

Table 4

The differences in net primary productivity (i.e., cproda) ($g/m^2/yr$) during the last month of June, in the one cut and three cut simulations, for the undisturbed and harvest treatments with pre-treatment thinning. Percent differences were calculated between the sawlog and WTH strategies.

Duration of Simulation (# of yrs)	Uncut	Sawlog	WTH	% Difference Between Sawlog & WTH
70	176.96	153.73	147.64	3.96
143	180.21	135.27	124.47	7.99

Table 5

The differences between final concentrations of C and N in four components of the forest system after 70- and 143-year simulations of the uncut and thinned harvest management treatments (month of June values are reported). Percent differences were calculated between the sawlog and WTH strategies.

	Forest Component	One Harvest (70 years)			Three Harvests (143 years)		
		Sawlog	*WTH*	% Difference	*Sawlog*	*WTH*	% Difference
C	*Vegetation*	5779.21	5373.13	7.03	6524.58	5592.91	14.28
	Soil	8931.64	8893.21	0.43	8994.04	8885.02	1.21
	Forest Floor	2374.67	2278.86	4.03	2553.17	2362.91	7.45
	Total System	17236.37	16688.02	3.18	18241.90	16985.07	6.89
N	*Vegetation*	29.91	28.04	6.25	32.62	28.39	12.97
	Soil	786.12	784.15	0.25	789.31	784.00	0.67
	Forest Floor	45.05	42.25	6.21	49.10	43.77	10.86
	Total System	861.95	855.24	0.78	872.03	856.96	1.73

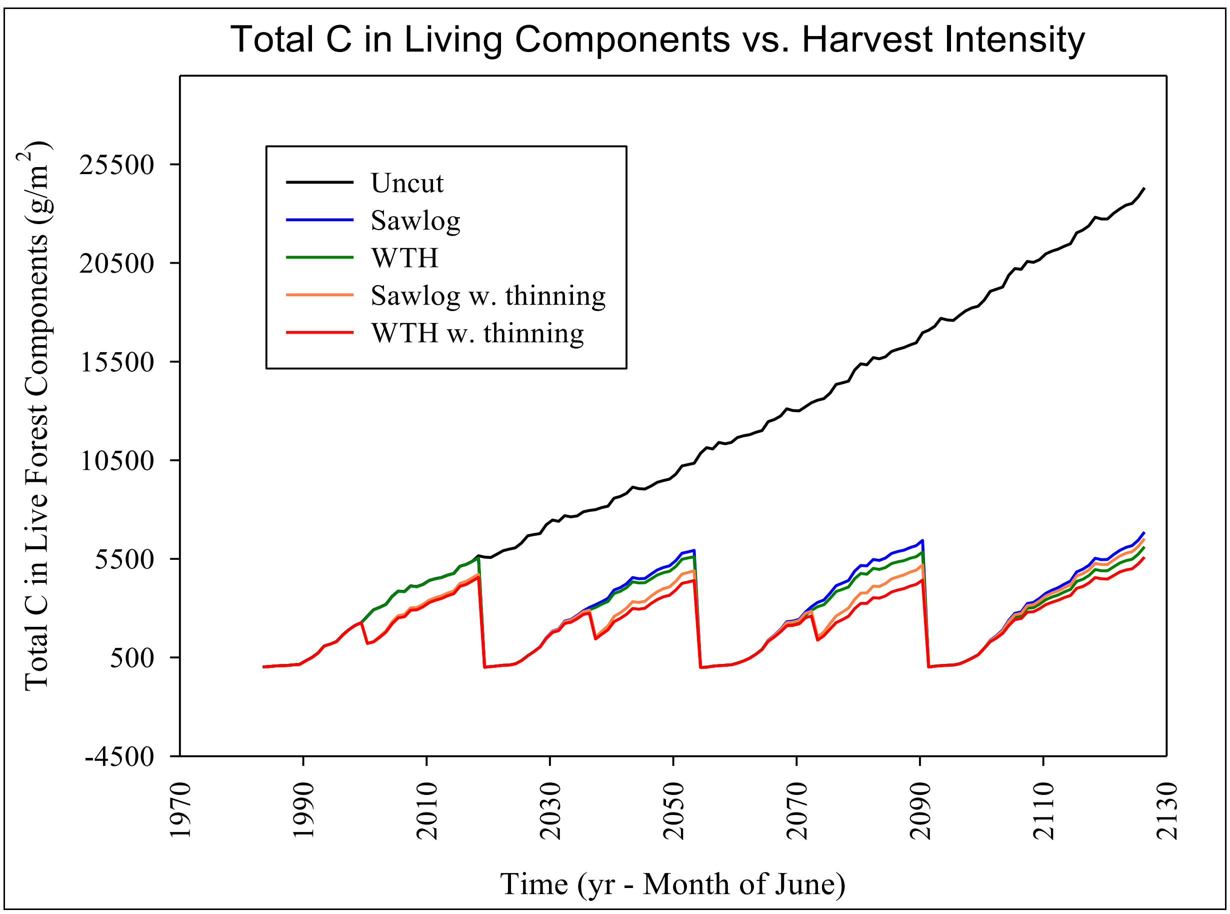

Figure 1. Month of June concentrations of C in forest vegetation from 1983 to 2126, during which four treatments were harvested at differing intensities in 2018, 2053, and 2087, and two were thinned in 2000, 2036, and 2072. The undisturbed values continuously increased, while all harvest treatments caused total

C to decrease to zero. C levels were able to increase back to pre-treatment concentrations for all harvest simulations, and C actually accumulated slowly in the sawlog treatments.

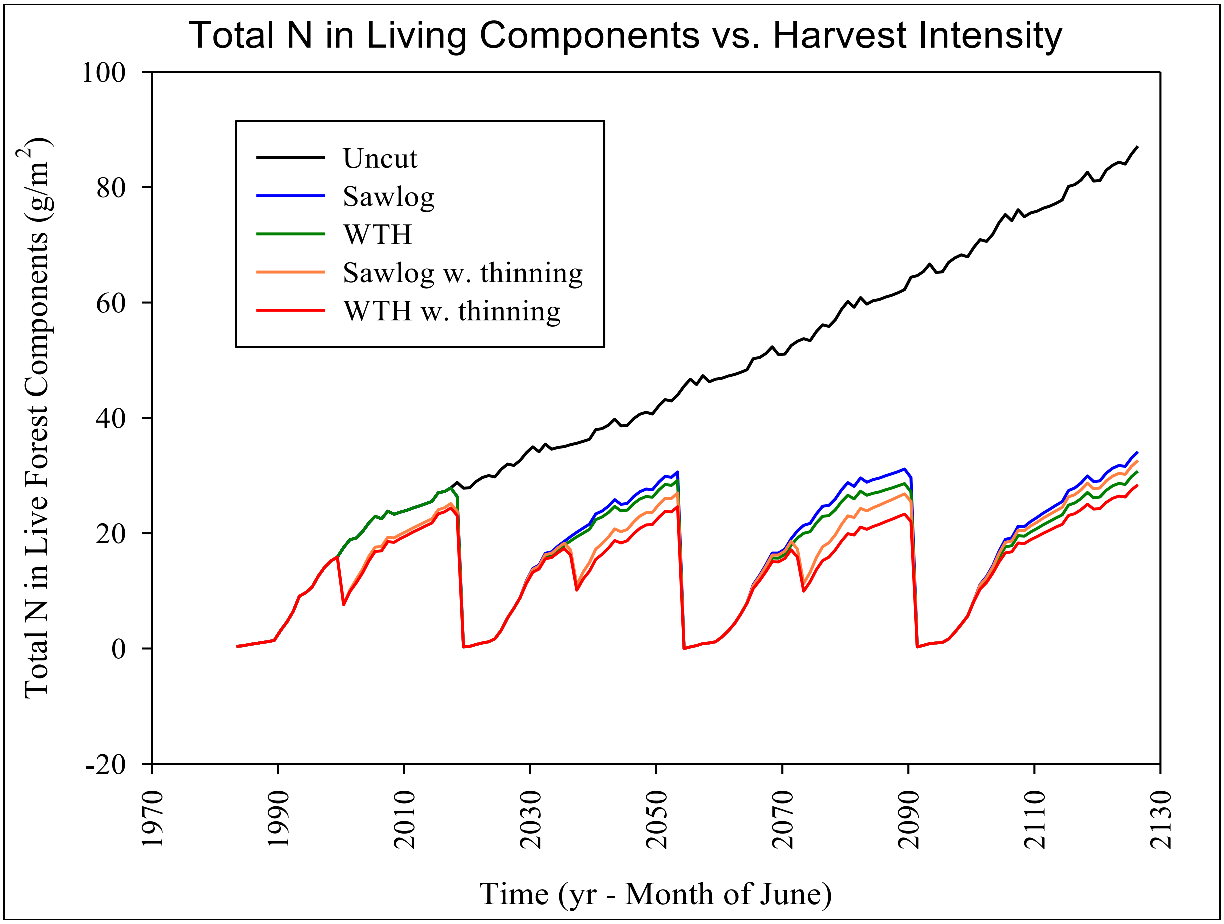

Figure 2. Month of June concentrations of N in forest vegetation from 1983 to 2126, during which four treatments were harvested at differing intensities in 2018, 2053, and 2087, and two were thinned in 2000, 2036, and 2072. The undisturbed values continuously increased, while all harvest treatments caused total N to decrease to zero. N levels were able to increase back to pre-treatment concentrations for all treatments except WTH with thinning, and N actually accumulated slowly in the sawlog treatments. The second harvest in the WTH with thinning strategy really affected the ecosystems ability to allocate N to the vegetation, seeing that the amount of N in the vegetation just before the third harvest was lower than that before the second.

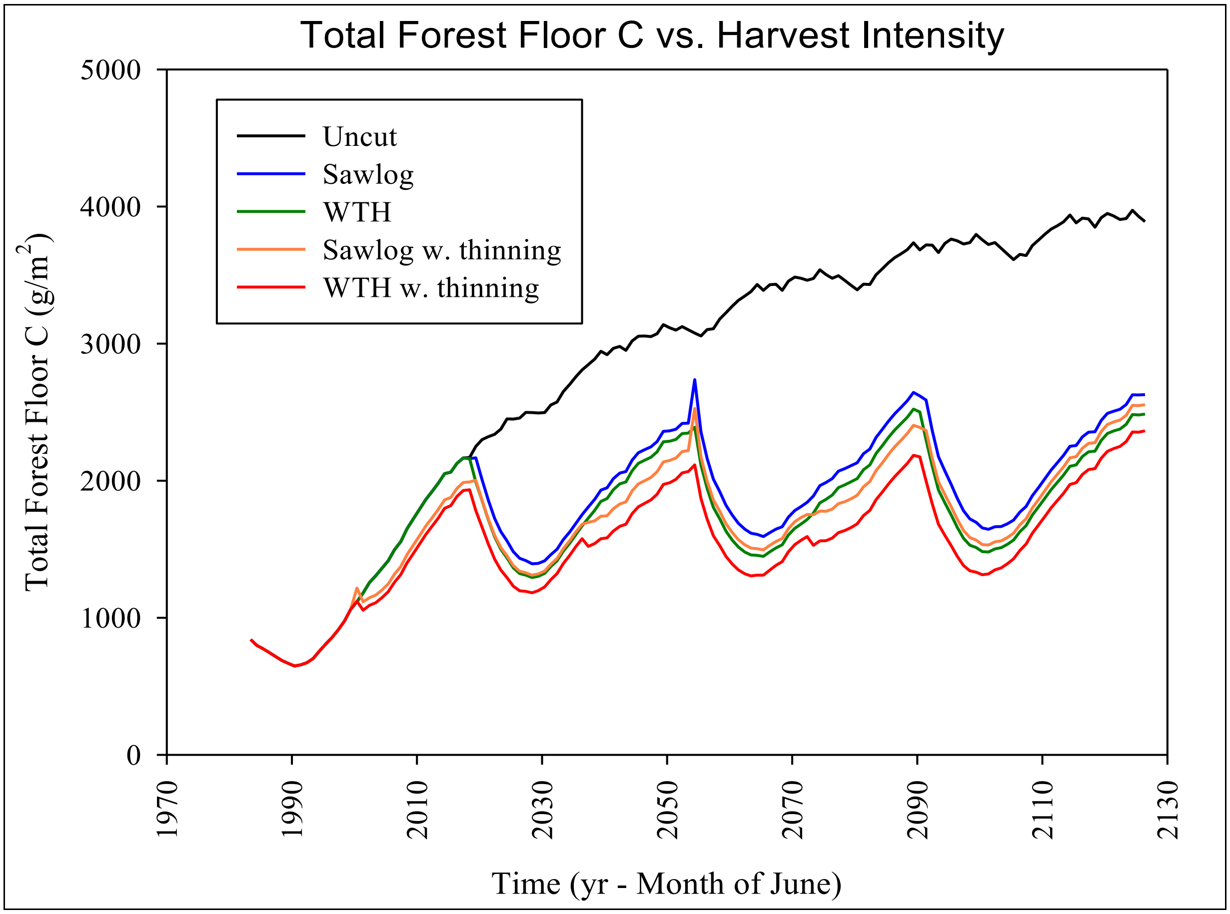

Figure 3. Month of June concentrations of C in forest vegetation from 1983 to 2126, during which four treatments were harvested at differing intensities in 2018, 2053, and 2087, and two were thinned in 2000, 2036, and 2072. The undisturbed values continuously increased, while all harvest treatments caused total C to decrease. C levels were able to increase back to pre-treatment concentrations for all treatments, and actually accumulated slowly in the forest floor over three harvests.

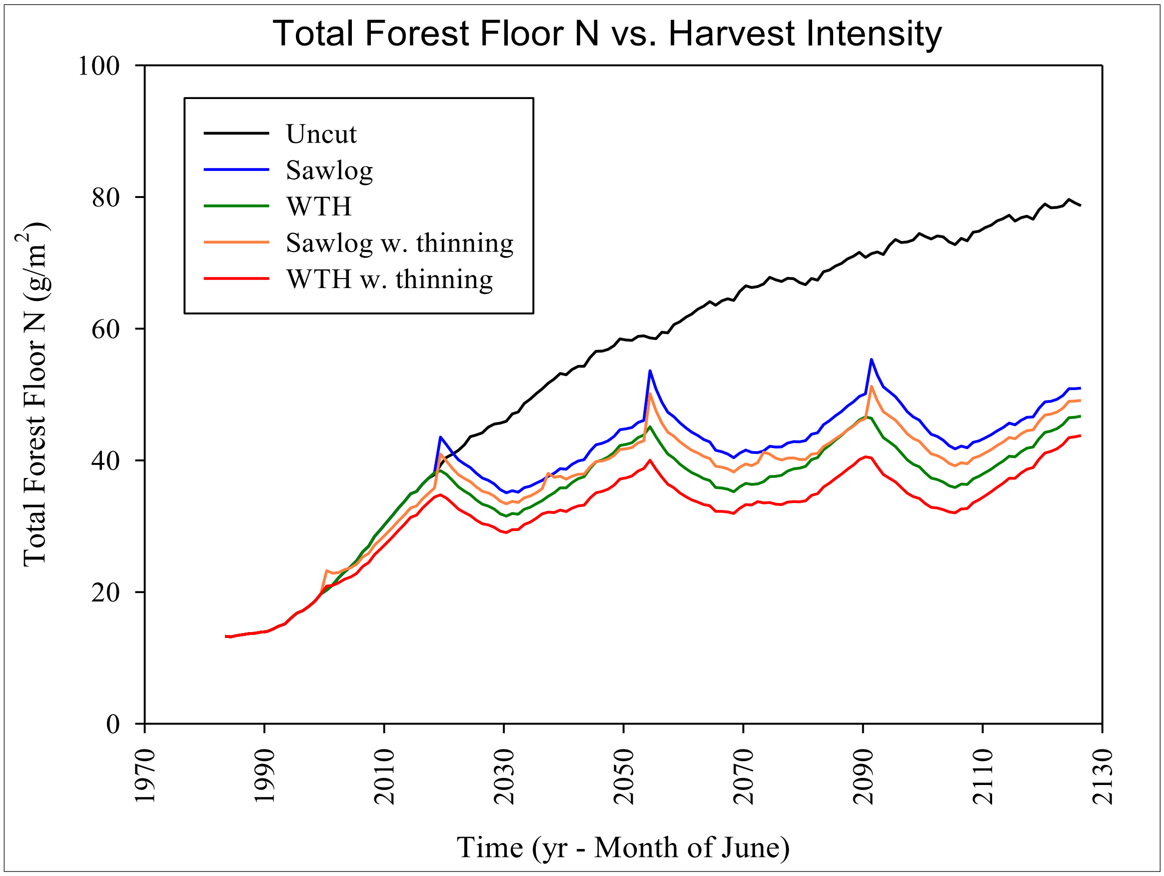

Figure 4. Month of June concentrations of N in forest vegetation from 1983 to 2126, during which four treatments were harvested at differing intensities in 2018, 2053, and 2087, and two were thinned in 2000, 2036, and 2072. The undisturbed values continuously increased, while all harvest treatments caused total N to decrease to zero. N levels were able to increase back to pre-treatment concentrations for all treatments, and actually accumulated slowly in all harvest strategy trends. Leaving the logging residue on the site caused N concentrations to spike in response to harvesting.

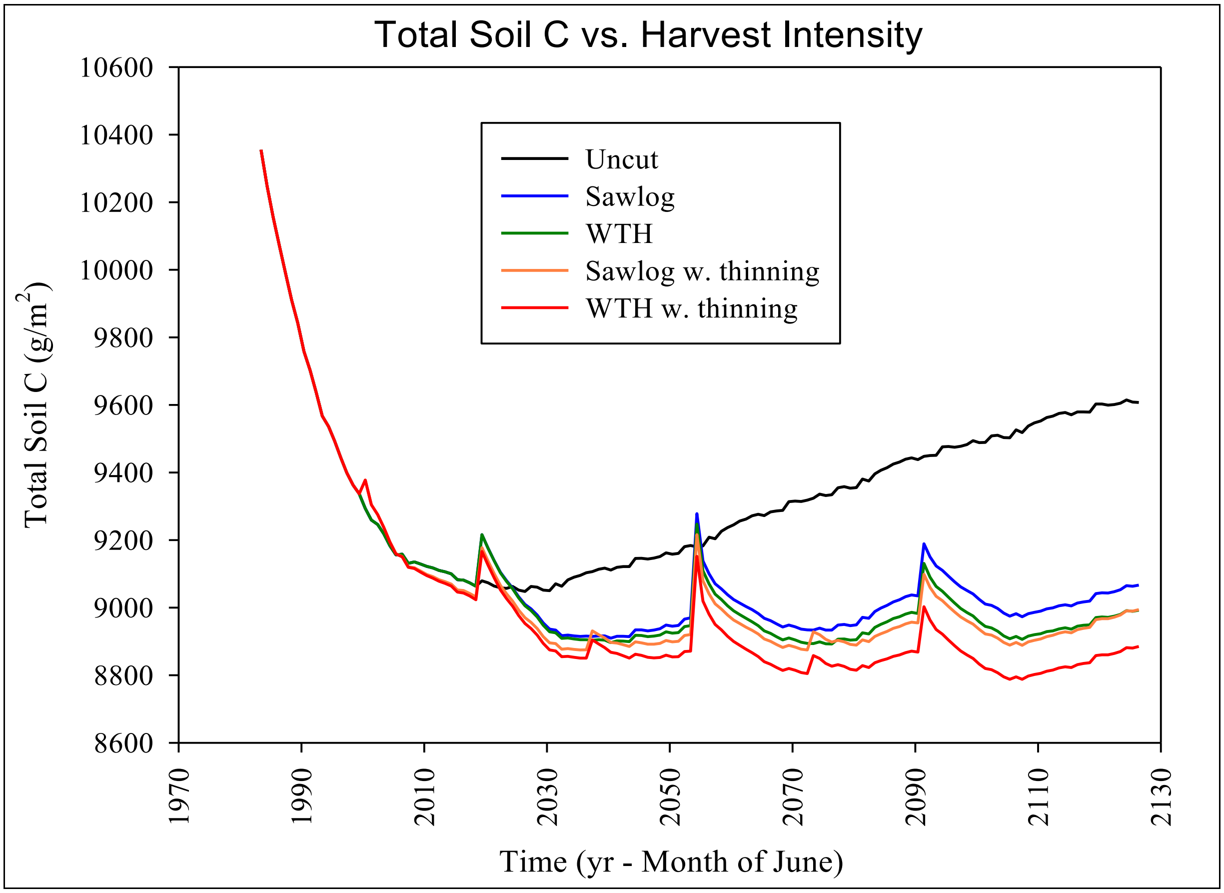

Figure 5. Month of June concentrations of soil C from 1983 to 2126, during which four treatments were harvested at differing intensities in 2018, 2053, and 2087, and two were thinned in 2000, 2036, and 2072. The undisturbed values gradually decreased until about 2020, followed by a continuously increasing trend. All harvest treatments caused total C to spike and then decline rapidly. After the first harvest, C was able to accumulate under all treatment conditions, except WTH with thinning. However, the second harvest affected this accumulation trend, and in all treatments the magnitude of the spike in response to harvesting decreased.

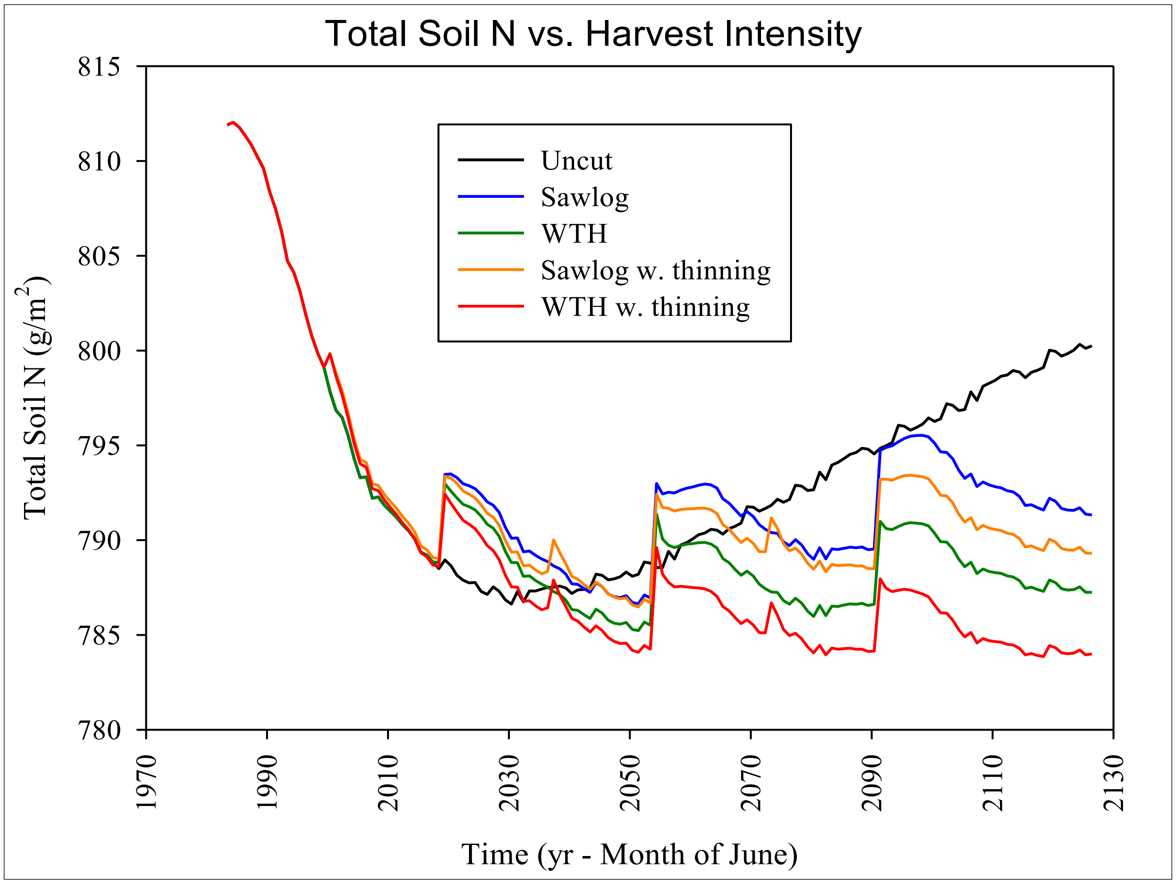

Figure 6. Month of June concentrations of soil N from 1983 to 2126, during which four treatments were harvested at differing intensities in 2018, 2053, and 2087, and two were thinned in 2000, 2036, and 2072. The undisturbed values gradually decreased until about 2020, followed by a continuously increasing trend in N concentrations. N accumulates in the soil over three harvests for both sawlog treatments, but the magnitude of the responsive spike continued to decrease when the WTH scenario was simulated.

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