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Predicted Effects of Prescribed Burning and Timber Management on Forest Recovery and Sustainability at Fort Benning, Georgia

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LIST OF ABBREVIATED TERMS

AGIN	annual aboveground woody growth increment (g m^{-2} yr^{-1})
AGROWTH	input to aboveground woody biomass (g m^{-2} yr^{-1})
AGRT:ST	ratio of belowground tree biomass to aboveground woody biomass
AGWB	aboveground woody biomass (g m^{-2})
AGWB%	aboveground wood biomass expressed as a percentage of maximum value
ATMN	atmospheric N deposition (g N m^{-2} yr^{-1})
BGROWTH	input to belowground tree root biomass (g m^{-2} yr^{-1})
BGWB	belowground tree root biomass (g m^{-2})
CONCN	plant tissue N concentration (g N g^{-1})
CUT	operator in the model that turns tree harvesting “on” or “off”
CUTFREQ	return interval of forest thinning or harvesting (years)
FIRE	operator in the model that turns prescribed burning “on” or “off”
FIREFRQ	return interval of prescribed burning
FIRELOSS	amount of soil C lost as a result of prescribed burning (g C m^{-2} yr^{-1})
fLEAF	fraction of aboveground biomass that is foliage
FRACOH	fraction of soil C stock in the O-horizon that is lost via prescribed burning
GRWTHMOD	factor modifying input to aboveground woody biomass (N feedback)
HARVST	removal of aboveground woody biomass by forest thinning or harvesting
HBAG	herbaceous aboveground biomass (g m^{-2})
HBAGDIFF	difference between minimum and maximum herbaceous aboveground biomass
HBAGMIN	minimum expected herbaceous aboveground biomass (g m^{-2})
HBBG	herbaceous belowground biomass (g m^{-2})
HBNREQ	annual N demand by herbaceous plants (g N m^{-2} yr^{-1})
HBRT:ST	herbaceous root biomass:shoot biomass ratio
HBRTMORT	annual mortality of herbaceous root biomass (g m^{-2} yr^{-1})
HBRTT	turnover time of herbaceous roots (years)
HBTF	fraction of N demand met by internal translocation in herbaceous plants
INITSOC	initial soil C stock (g C m^{-2})
LEAFTT	turnover time of tree foliage (years)
LFBMSS	tree leaf biomass (g m^{-2})
LFLIT	annual leaf litterfall (g m^{-2})
LITIN	total annual aboveground and belowground litter production (g m^{-2} yr^{-1})
NMINFLUX	annual flux of net soil N mineralization (g N m^{-2} yr^{-1})
NMINRATE	annual rate of net soil N mineralization (yr^{-1})
PEN	potential excess N (g N m^{-2})
PLNTNREQ	total annual plant N demand (g N m^{-2} yr^{-1})
REMOVAL	percent of aboveground woody biomass removed by thinning or harvest
RTMORT	annual removal of belowground biomass by tree root mortality (g m^{-2} yr^{-1})
RTTT	turnover time of tree root biomass (years)
SOC	soil C stock (g C m^{-2})
SOCIN	annual soil C inputs (g C m^{-2} yr^{-1})

SOCOUT	annual soil C losses (g C m^{-2} yr^{-1})
SOCTT	turnover time of soil C stock (years)
SOILC:N	soil C:N ratio
SOILN	soil N stock (g N m^{-2})
TARGET	maximum aboveground woody biomass (g m^{-2})
TRNREQ	annual N demand of forest trees (g N m^{-2} yr^{-1})
WDYTF	fraction of annual N demand met by internal translocation in trees
SERDP	Strategic Environmental Research and Development Program
SEMP	SERDP Ecosystem Management Program

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SUMMARY

The objective of this work was to use a simple compartment model of soil carbon (C) and nitrogen (N) dynamics to predict forest recovery on degraded soils and forest sustainability, following recovery, under different regimes of prescribed fire and timber management. This report describes the model and a model-based analysis of the effect of prescribed burning and forest thinning or clearcutting on stand recovery and sustainability at Fort Benning, GA. I developed the model using Stella® Research Software (High Performance Systems, Inc., Hanover, NH) and parameterized the model using data from field studies at Fort Benning, literature sources, and parameter fitting. The model included (1) a tree biomass submodel that predicted aboveground and belowground tree biomass, (2) a litter production submodel that predicted the dynamics of herbaceous aboveground and belowground biomass, (3) a soil C and N submodel that predicted soil C and N stocks (to a 30 cm soil depth) and net soil N mineralization, and (4) an excess N submodel that calculated the difference between predicted plant N demands and soil N supplies. There was a modeled feedback from potential excess N (PEN) to tree growth such that forest growth was limited under conditions of N deficiency.

Two experiments were performed for the model-based analysis. In the first experiment, forest recovery from barren soils was predicted for 100 years with or without prescribed burning and with or without timber management by thinning or clearcutting. In the second experiment, simulations began with 100 years of predicted forest growth in the absence of fire or harvesting, and sustainability was predicted for a further 100 years either with or without prescribed burning and with or without forest management. Four performance variables (aboveground tree biomass, soil C stocks, soil N stocks, and PEN) were used to evaluate the predicted effects of timber harvesting and prescribed burning on forest recovery and sustainability.

Predictions of forest recovery and sustainability were directly affected by how prescribed fire affected PEN. Prescribed fire impacted soil N supplies by lowering predicted soil C and N stocks which reduced the soil N pool that contributed to the predicted annual flux of net soil N mineralization. On soils with inherently high N availability, increasing the fire frequency in combination with stand thinning or clearcutting had little effect on predictions of forest recovery and sustainability. However, experiments with the model indicated that combined effects of stand thinning (or clearcutting) and frequent prescribed burning could have adverse effects on forest recovery and sustainability when N availability was just at the point of limiting forest growth. Model predictions indicated that prescribed burning with a 3-year return interval would decrease soil C and N stocks but not adversely affect forest recovery from barren soils or sustainability following ecosystem recovery. On soils with inherently low N availability, prescribed burning with a 2-year return interval depressed predicted soil C and N stocks to the point where soil N deficiencies prevented forest recovery as well as forest sustainability following recovery.

Keywords: soil carbon and nitrogen, forest recovery, forest sustainability, ecosystem modeling, fire, thinning, clearcutting, degraded soils, military land management

1. INTRODUCTION

Military land managers are faced with the challenge of using a given amount of land for the purpose of training and troop readiness. This mission must be accomplished in an ecologically sound manner that meets military requirements and, at the same time, promotes ecosystem sustainability so that military activities are not compromised by a degraded landscape. One aspect of ecosystem sustainability is preserving natural resources on a landscape that may be intensively used for military training. A second aspect involves restoring terrestrial ecosystems on soils that have been degraded by continuous military use. Military activities that can potentially result in degraded lands include the use of heavy weapons, and off-road wheeled, and tracked vehicle training.

Disturbance of soil physical properties and soil structure are commonly reported effects associated with use of heavy machinery in forestry (Hatchell et al., 1970) and military training (Iverson et al., 1981; Prose, 1985; Braunack, 1986; Thurow et al., 1993). At Fort Benning, GA, field training with tracked vehicles has resulted in an overall loss of soil quality at some training sites (Garten et al., 2003). Barren, heavily disturbed soils have negligible O-horizons, lower soil N availability, and lower C and N stocks than soils subject to minimal military use (Garten and Ashwood, 2004a). In some environments, the effects of soil disturbance by military vehicles can persist for decades (e.g., Iverson et al., 1981). This leads to questions about how land management practices affect ecosystem recovery following soil disturbance.

Land management at Fort Benning includes the use of prescribed fire and tree thinning or clearcutting to promote healthy forests. For example, prescribed fire is a common land management practice to clear herbaceous and woody shrubs from beneath forest stands because it improves access for military training and timber management and reduces the fuel load that might otherwise contribute to wildfires. Burning also helps to restore and maintain fire-dependent plant communities (e.g., longleaf pine) that are important habitat for threatened and endangered species at Fort Benning. One of the installation's forest management goals is to restore fire-dependent longleaf pine communities, and to meet this goal ≈10,000 ha are subject to prescribed burning each year. Each training compartment at Fort Benning is burned, on average, once every 3 years (the range is once a year to once every 5 years). The red-cockaded woodpecker recovery plan requires controlled burns approximately every 3 years in habitat used by that endangered species. In addition to restoration of longleaf pine, timber management at Fort Benning generally involves thinning pine and pine/hardwood forests (≈2,800 ha yr^{-1}) and clearcutting of diseased or insect-damaged stands. Current forest management guidelines include maintenance of a 100 year harvest rotation for healthy loblolly and shortleaf pine if threatened or endangered wildlife species are not adversely impacted by forest removal (Swiderek et al., 2002).

The challenge of military land use in the southeastern US is further complicated by the potential effects of prescribed fire and timber management on highly weathered, coarse-textured Ultisols. The complexity of land management on such nutrient poor soils raises questions about how possible interactions between soil N availability, prescribed burning, and forest harvesting may limit ecosystem recovery on degraded land or prevent ecosystem sustainability following forest recovery. These questions are difficult to answer with field experiments because: (1) the study of ecosystem recovery requires a prolonged period of measurements, and (2) replication of such long-term experiments can be problematic. The objective of this research was to use a simple compartment model of soil carbon (C) and nitrogen (N) dynamics to predict forest recovery on degraded soils and forest sustainability, following recovery, under different regimes of prescribed fire and timber management. This report describes the model and a model-based analysis of the effect of prescribed burning and forest thinning or clearcutting on stand recovery and sustainability for two different soil types at Fort Benning, GA. The model was parameterized for a generalized forest cover and it is potentially useful for predicting both the recovery of forest biomass and soil quality on degraded land.

2. METHODS

2.1 STUDY SITE

Fort Benning was established by the US military near Columbus, GA, in 1918 and considerable additional land was added to the installation in 1941. The number of troops onsite ranges between 18,000 and 23,000 annually. The land area at Fort Benning is ≈73,600 ha, and land use prior to acquisition by the US Government was primarily a mixture of agriculture and forestry. Current land cover at Fort Benning is ≈49% mixed forest, 25% deciduous forest, 10% barren or developed land, 7% evergreen forest, 6% herbaceous grassland, 2% shrub land, and 1% water (Jones and Davo, 1997). Mean annual temperature in the Columbus area is 18.3 °C and mean annual precipitation is 130 cm.

Soils at the site are highly weathered Ultisols, mostly of Coastal Plain origin but with some minor inclusion of alluviums derived from the Piedmont ecological unit to the north. The two dominant Coastal Plain ecological units that cover most of the installation are Sand Hills and Upper Loam Hills. The major soil series associated with these soil units are Ailey loamy coarse sand, Cowarts loamy sand, Nankin sandy clay loam, Pelion loamy sand, Troup, Troup loamy fine sand, Vaucluse, and Vaucluse sandy loam. Sands and loamy sands are common on upland sites while sandy loams and sandy clay loams are commonly found in valleys and riparian areas. Further details on the biology, geology, physical setting, and history of Fort Benning are available elsewhere (Jones and Davo, 1997).

2.2 MODEL STRUCTURE

2.2.1 Software Platform

I developed the model using Stella® Research Software (High Performance Systems, Inc., Hanover, NH) Version 7.0.2 for Power Macintosh computers. The first-order differential equations, of the general form dx/dt = fluxes into a compartment - fluxes from a compartment, were solved on an annual time step with Euler's integration method. Although Euler's method is less precise than Runge-Kutta methods, its use was mandated by certain "if-then" type statements in the model. In this report, model equations are presented in Stella® language format. This will facilitate reproduction of the model by other investigators using Stella® software. Throughout this report, variable names are identified by abbreviations with all capital letters.

2.2.2 Tree Biomass Submodel

The tree biomass submodel (Fig. 1) had two state variables: (1) aboveground woody biomass (AGWB, g m^{-2}), and (2) belowground root biomass (BGWB, g m^{-2}). The change in AGWB was calculated as:

$$AGWB(t) = AGWB(t-dt) + (AGROWTH - HARVST) \cdot dt \quad [1]$$

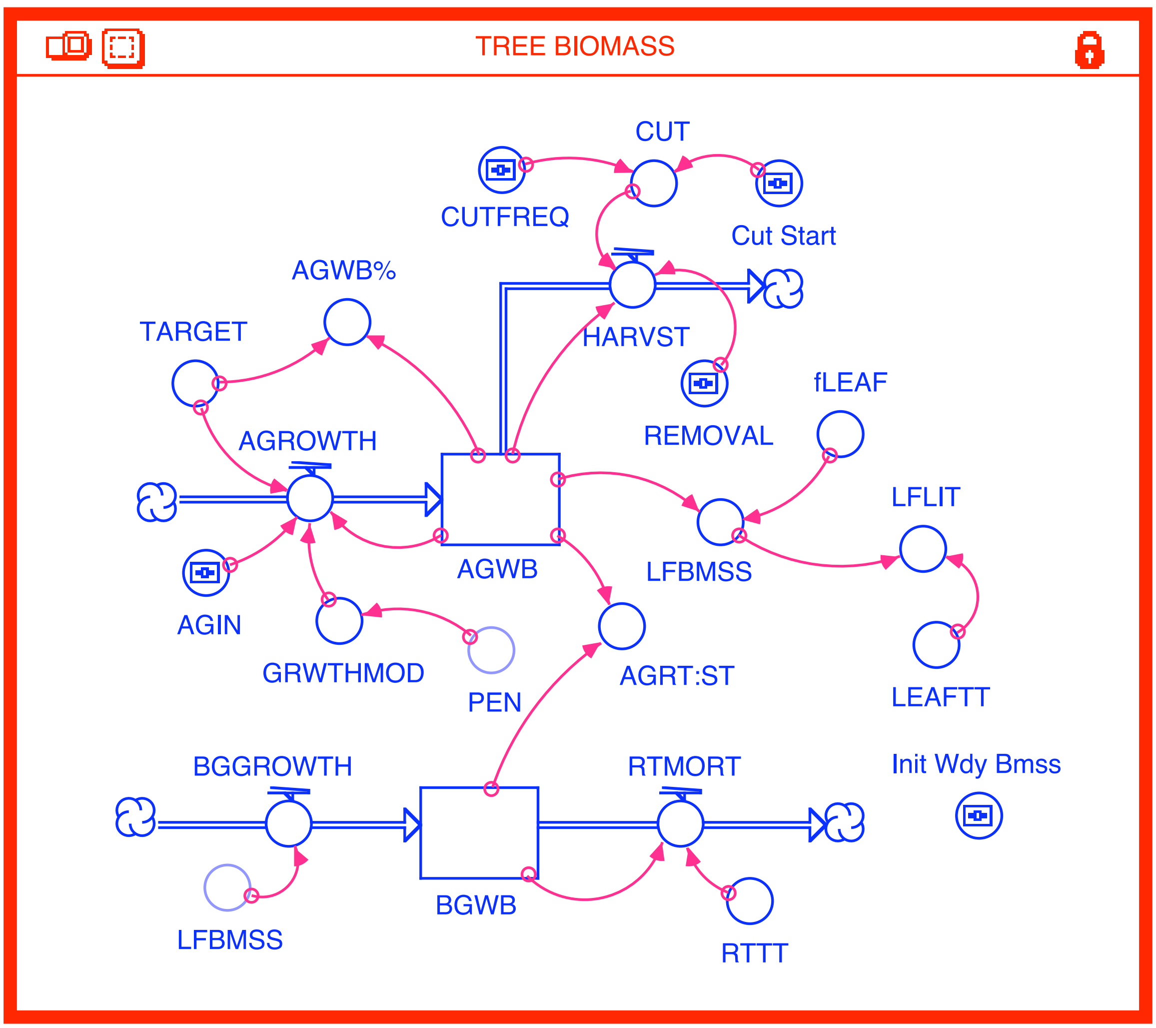

Fig. 1. Tree biomass submodel in Stella® model format.

where AGROWTH (g m^{-2} yr^{-1}) is the input to AGWB and HARVST is removal of AGWB by forest thinning or harvesting. AGROWTH was calculated as:

$$AGROWTH = (AGIN \cdot ((TARGET - AGWB)/(TARGET))) \cdot GRWTHMOD \quad [2]$$

where AGIN (g m^{-2} yr^{-1}) is the annual aboveground woody growth increment, TARGET (g m^{-2}) is the maximum aboveground woody biomass, and GRWTHMOD is a modifier that allows for the feedback of N availability on AGROWTH. GRWTHMOD was represented as:

$$GRWTHMOD = \text{if } PEN < 0.0 \text{ then } 0 \text{ else } 1 \quad [3]$$

where PEN (g N m^{-2}) is potential excess N. The modifier set AGROWTH to zero if PEN was less than zero. Otherwise, AGROWTH assumed its full calculated value.

The thinning or harvest of AGWB was calculated as:

$$HARVST = \text{if } CUT = 1 \text{ then } (AGWB \cdot (REMOVAL/100)) \text{ else } 0 \quad [4]$$

where REMOVAL was the percent of AGWB removed. HARVST was triggered when CUT = 1 and the latter variable was represented by pulse function with a recurring harvest frequency (CUTFREQ) in the model. When CUTFREQ assumed any value other than 1, there was no loss of AGWB through harvesting.

Tree leaf biomass (LFBMSS, g m^{-2}) was calculated as the product of AGWB and the fraction of aboveground biomass that was foliage (fLEAF). Annual leaf litterfall (LFLIT, g m^{-2} yr^{-1}) was calculated as:

$$LFLIT = LFBMSS \cdot (1/LEAFTT) \quad [5]$$

where LEAFTT was the turnover time (years) of tree foliage.

The change in BGWB (g m^{-2}) was calculated as:

$$BGWB(t) = BGWB(t-dt) + (BGGROWTH - RTMORT) \cdot dt \quad [6]$$

where BGROWTH (g m^{-2} yr^{-1}) is the input to BGWB and RTMORT (g m^{-2} yr^{-1}) is the removal of BGWB by root mortality. BGROWTH was assumed to be equivalent to LFBMSS. RTMORT was calculated as:

$$RTMORT = BGWB \cdot (1/RTTT) \quad [7]$$

where RTTT was the turnover time (years) of root biomass.

For convenience, two other variables were calculated by the model: (1) AGRT:ST or the ratio of BGWB to AGWB, and (2) AGWB% or the amount of AGWB expressed as a percentage of the TARGET aboveground woody biomass. At steady state, AGRT:ST was ≈0.25.

2.2.3 Litter Production Submodel

The litter production submodel (Fig. 2) represented the dynamics of herbaceous aboveground and belowground biomass and calculated litter inputs to the soil C submodel. Herbaceous aboveground biomass (HBAG, g m^{-2}) was calculated as:

$$HBAG = ((1-(AGWB/TARGET)) \bullet HBAGDIFF) + HBAGMIN \quad [8]$$

where HBAGDIFF (g m^{-2}) is the difference between minimum and maximum expected herbaceous aboveground biomass and HBAGMIN (g m^{-2}) is the expected minimum herbaceous aboveground biomass. The equation makes herbaceous aboveground biomass decline from a maximum to a minimum value with the development of AGWB. Herbaceous belowground biomass (HBBG, g m-2) was calculated as the product of HBAG and a root:shoot ratio (HBRT:ST). The mortality of herbaceous root biomass (HBRTMORT, g m^{-2} yr^{-1}) was calculated as:

$$HBRTMORT = HBBG \bullet (1/HBRTT) \quad [9]$$

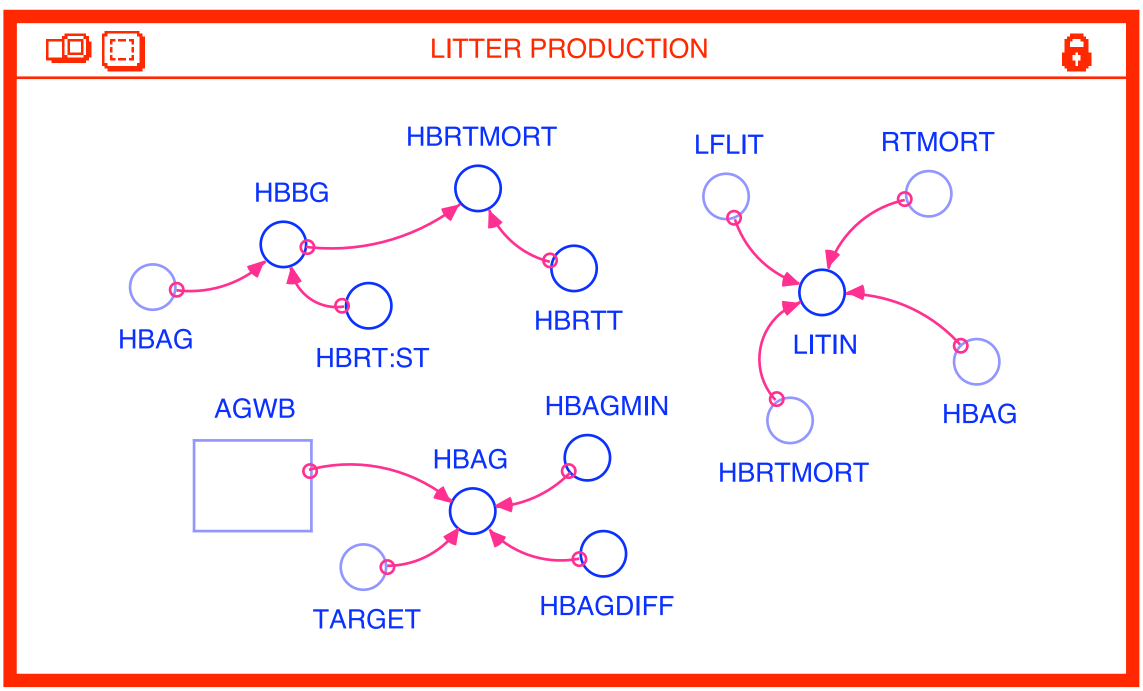

Fig. 2. Litter production submodel in Stella® model format.

where HBRTT (years) is the turnover time of herbaceous roots. Finally, total annual aboveground and belowground litter production (LITIN, g m^{-2} yr^{-1}) was calculated as:

$$LITIN = LFLIT + HBAG + HBRTMORT + RTMORT \quad [10]$$

The latter equation assumes that each year all herbaceous aboveground biomass dies and is returned to the surface soil.

2.2.4 Soil Carbon and Nitrogen Submodel

Soil C (SOC, g C m^{-2}) was represented by a single compartment that included both O-horizons and the surface 30 cm of mineral soil (Fig. 3). The change in SOC was calculated as:

$$SOC(t) = SOC(t-dt) + (SOCIN - SOCOUT - FIRELOSS) \cdot dt \quad [11]$$

where SOCIN (g C m^{-2} yr^{-1}) denotes soil C inputs, SOCOUT (g C m^{-2} yr^{-1}) denotes soil C losses through organic matter decomposition, and FIRELOSS (g C m^{-2} yr^{-1}) is the amount of soil C lost as a result of prescribed burning. SOCIN was calculated as the product of plant tissue C concentration (0.5 g C g^{-1}) and LITIN. SOCOUT was calculated as:

$$SOCOUT = SOC \cdot (1/SOCTT) \quad [12]$$

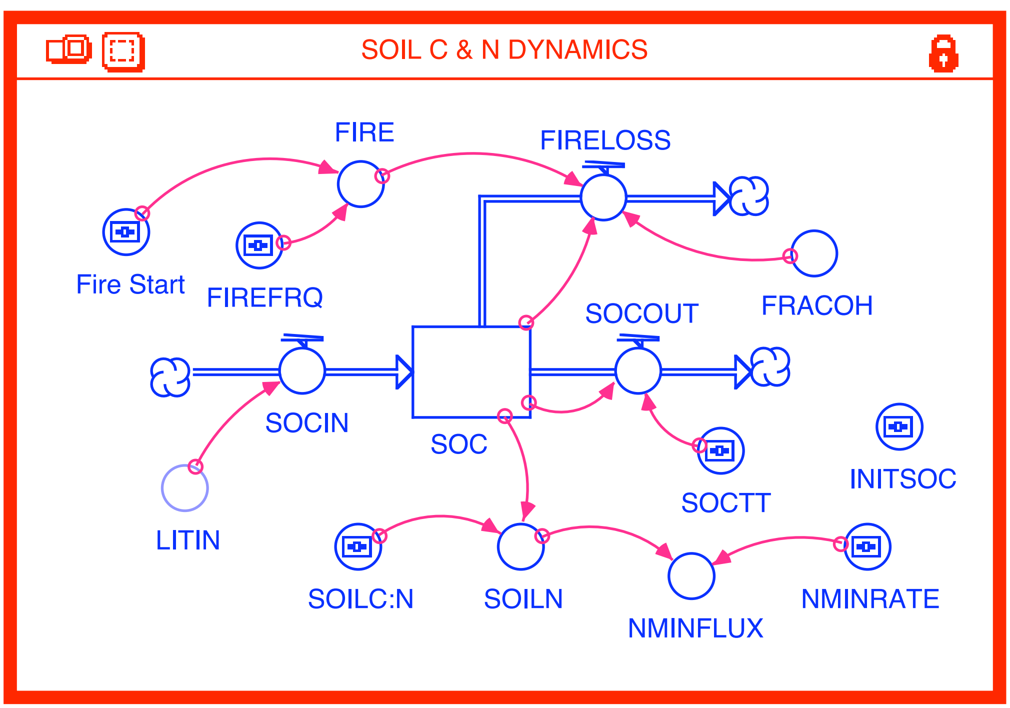

Fig. 3. Soil C and N submodel in Stella® model format.

where SOCTT (years) is the turnover time of soil C. Initial soil C stocks (INITSOC, g C m^{-2}) were set at the beginning of a model run accordant with the starting soil quality.

FIRELOSS in the soil C and N submodel was calculated as:

$$FIRELOSS = SOC \cdot FIRE \cdot FRACOH \quad [13]$$

where FRACOH is the fraction of soil C in the O-horizon that is lost during a prescribed burn. FIRE was represented by a pulse function that set FIRE equal to unity whenever prescribed burning occurred (otherwise FIRE = 0). A separate variable, FIREFRQ (years), was used to establish the return interval of prescribed burning.

Soil N (SOILN, g N m^{-2}) was calculated by dividing SOC by the soil C:N ratio (SOILC:N). The net flux of net soil N mineralization (NMINFLUX, g N m^{-2} yr^{-1}) or the amount of soil organic N that is annually transformed to NH_4-N and NO_3-N was calculated as the product of SOILN and the net soil N mineralization rate (NMINRATE, yr^{-1}).

2.2.5 Excess Nitrogen Submodel

Potential excess N (PEN, g N m^{-2}) was calculated as the difference between N inputs and outputs to a pool of plant-available soil N (Fig. 4). PEN was calculated as:

$$PEN = ATMN + NMINFLUX - PLNTNREQ \quad [14]$$

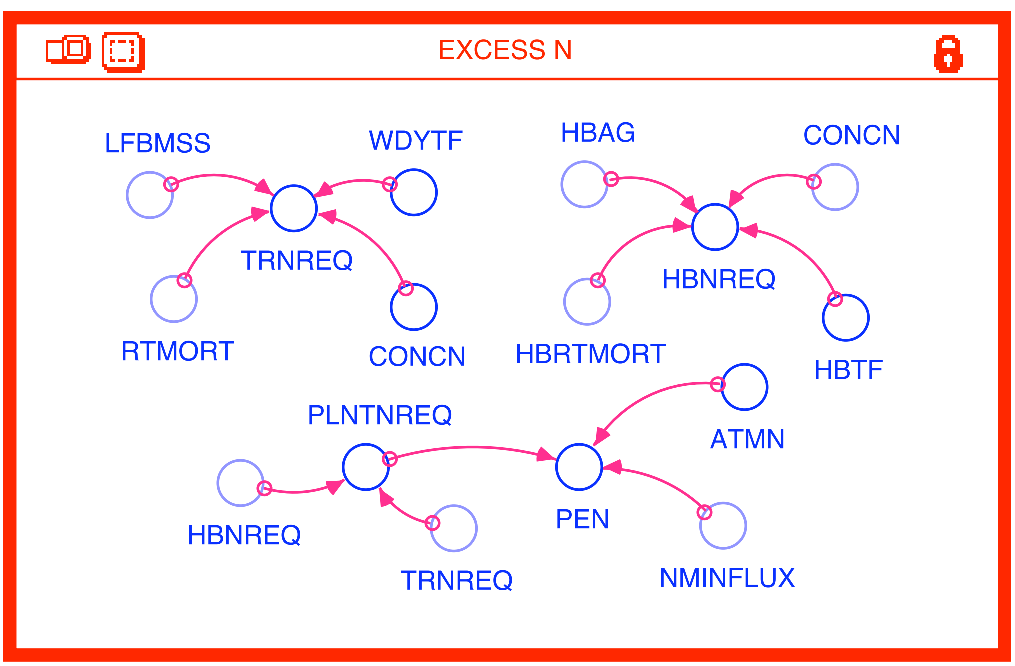

Fig. 4. Potential excess N submodel in Stella® model format.

where ATMN was total atmospheric N deposition (g N m^{-2} yr^{-1}), NMINFLUX is the net flux of soil N mineralization, and PLNTNREQ (g N m^{-2} yr^{-1}) is the annual plant N requirement.

The N demand of herbaceous plants (HBNREQ, g N m^{-2} yr^{-1}) was calculated as:

$$HBNREQ = ((HBAG + HBRTMORT) \cdot (CONCN/100) \cdot (1 - HBTF) \qquad [15]$$

where HBTF is the fraction of the N demand met by internal N translocation within herbaceous plants, and CONCN (g N g^{-1}) is the plant tissue N concentration. The equation assumes herbaceous aboveground biomass regrows annually. The N demand of forest trees (TRNREQ, g N m^{-2} yr^{-1}) was calculated as:

$$TRNREQ = (LFBMSS + RTMORT) \cdot (CONCN/100) \cdot (1 - WDYTF) \qquad [16]$$

where WDYTF is the fraction of N demand met by internal tree N translocation.

Total plant N demand (PLNTNREQ, g N m^{-2} yr^{-1}) was calculated as the sum of HBNREQ and TRNREQ. Equations for predicting HBNREQ and TRNREQ both assume: (1) belowground tree biomass production is in approximate balance with tree root mortality, and (2) new biomass production above and belowground has roughly the same tissue N concentration.

2.3 MODEL PARAMETERIZATION

The model was parameterized using information from field studies at Fort Benning (Garten and Ashwood, 2004a; 2004b), literature sources, and parameter fitting. Prior research (Garten and Ashwood, 2004b) indicated that soils with varying sand content had different predicted thresholds to ecosystem recovery at Fort Benning. Predicted thresholds to recovery were less on soils with more than 70% sand content, apparently due to higher relative rates of net soil N mineralization in more sandy soils. Consequently, the model was parameterized for soils with > 70% sand (identified as “more sandy” or “high soil N availability”) and < 70% sand (identified as “less sandy” or “less soil N availability”).

2.3.1 Tree Biomass Submodel

Parameters associated with the tree biomass submodel are presented in Table 1. Aboveground woody growth increment (AGIN) was set to 1000 g m^{-2} yr^{-1}. At this growth rate, predicted aboveground forest biomass (AGWB) reached 94% of steady state in ≈50 years. Maximum aboveground tree biomass (TARGET) was set to 18000 g m^{-2} which is in agreement with estimates of aboveground biomass in longleaf pine stands at Fort Benning (Garten and Ashwood, 2004b), in agreement with stand biomass in mature (45 year old) forests on the southern Piedmont (≈18000 g m^{-2} based on data in Johnson and Lindberg, 1992), and similar to aboveground biomass in loblolly pine after 50 to 60 years of stand development (≈21000 g m^{-2};

Table 1. Parameter values for variables in the tree biomass submodel			
Variable	Abbreviation	Units	Value
Aboveground woody growth increment	AGIN	g m^{-2} yr^{-1}	1000
Fraction of aboveground tree biomass in foliage	fLEAF	fraction	0.023
Harvest frequency	CUTFREQ	years	0 to 100[a]
Tree leaf turnover	LEAFTT	years	1
Percent of tree biomass removed at harvest	REMOVAL	%	0 to 99[a]
Turnover time of tree root biomass	RTTT	years	10
Maximum aboveground tree biomass	TARGET	g m^{-2}	18000
[a]Depending on the simulation, the value varied within the indicated range.			

Switzer et al., 1968). The maximum aboveground tree biomass selected for Fort Benning is also in the range of aboveground biomass densities of saw timber stands and forest stands in advanced stages of recovery (following forest clearing) in the eastern US (Brown et al., 1997). Depending on the simulation, the interval between stand harvests (CUTFREQ) varied from 0 to 100 years and the percent of tree biomass removed at harvest (REMOVAL) varied from 0 to 99%. It was assumed that stand thinning operations removed 50% of the aboveground tree biomass.

The fraction of aboveground tree biomass represented by foliage (fLEAF) was set to 0.023 based on data from southeastern forests (Johnson and Van Hook, 1989; Johnson and Lindberg, 1992) indicating that leaf biomass is typically 2 to 5% of total aboveground biomass. Using this fraction, the predicted steady state tree leaf biomass (LFBMSS) was 414 g m^{-2} which is in good agreement with estimates of annual leaf litterfall in the southeastern US (Sharpe et al., 1980). Tree leaf turnover time (LEAFTT) was assumed to be one year and the turnover time of tree root biomass (RTTT) was set to 10 years (Gill and Jackson, 2000).

2.3.2 Litter Production Submodel

Parameters associated with the litter production submodel are presented in Table 2. The minimum herbaceous aboveground biomass (HBAGMIN) was set to 150 g m^{-2} based on

Table 2. Parameter values for variables in the litter production submodel			
Variable	Abbreviation	Units	Value
Difference between minimum and maximum herbaceous aboveground biomass	HBAGDIFF	g m^{-2}	200
Minimum herbaceous aboveground biomass	HBAGMIN	g m^{-2}	150
Herbaceous root:shoot ratio	HBRT:ST	fraction	1
Herbaceous root turnover time	HBRTT	years	2

measured standing biomass of ground cover in longleaf pine stands on xeric sites (Kirkman et al., 2001). In the model, herbaceous aboveground biomass increased with decreasing aboveground tree biomass, and HBAGMIN was the predicted amount of herbaceous aboveground biomass in mature forests. The difference between minimum and maximum herbaceous aboveground biomass was set to 200 g m^{-2}. Other studies (Odum, 1960) indicate that ≈360 g m^{-2} is a reasonable value for aboveground oldfield biomass in Georgia. The model predicted 350 g m^{-2} herbaceous aboveground biomass when aboveground tree biomass was at its minimum. The root:shoot ratio for herbaceous biomass (HBRT:ST) was set to 1.0 based on studies by Kelly (1975) who measured root:shoot ratios of 0.78 and 1.4 in two east Tennessee old field communities. The turnover time of herbaceous plant roots (HBRTT) was set to 2 years on the basis of an average root turnover time in grasslands (Gill and Jackson, 2000).

2.3.3 Soil Carbon and Nitrogen Submodel

Parameters associated with the soil C and N submodel are presented in Table 3. Prior field work (Garten and Ashwood, 2004b) indicated that Fort Benning soils have a high sand content (on average, 70% sand; two-thirds of 129 soil samples collected onsite had a sand content that exceeded 70%). The turnover time of soil C (SOCTT) in these coarse textured soils, that offer little physical protection from decomposition of soil organic matter, was set to 10 years. Both net soil N mineralization rates (NMINRATE) and soil C:N ratios (SOILC:N) varied depending on soil type (Garten and Ashwood, 2004b). Based on field measurements, the rate of net soil N mineralization was 0.026 and 0.064 yr^{-1}, respectively, on less sandy (< 70% sand content) and more sandy (> 70% sand content) soils. The mean soil C:N ratio was 21 on less sandy soils and 36 on more sandy soils (Garten and Ashwood, 2004b).

Table 3. Parameter values for variables in the soil C and N submodel

Variable	Abbreviation	Units	Value	
			Less sandy soils	More sandy soils
Frequency of prescribed fire	FIREFREQ	years	0 to 3[a]	0 to 3[a]
Fraction of soil C lost in fire	FRACOH	fraction	0.12	0.12
Initial soil C on barren land	INITSOC	g C m^{-2}	630	630
Net soil N mineralization	NMINRATE	$year^{-1}$	0.026	0.064
Soil C turnover time	SOCTT	years	10	10
Soil C:N ratio	SOILC:N	ratio	21	36

[a]Depending on the simulation,the value was varied within the indicated range

The frequency of prescribed fire was varied depending on the model scenario. The fraction of soil C in O-horizons at Fort Benning is ≈12% (Garten and Ashwood, 2004b) and the impact of ground fires is limited primarily to O-horizons. For the purpose of simulating fire effects, it was assumed that the fraction of soil C lost during prescribed burning (FRACOH) was equivalent to the fraction of soil C residing in the O-horizon. Each simulation discussed in this report started from barren land, and initial soil C stocks (INITSOC) were set to 630 g C m^{-2} based on data from 14 barren sites at Fort Benning (Garten and Ashwood, 2004b).

2.3.4 Excess Nitrogen Submodel

The parameters associated with the excess N submodel are presented in Table 4. Data on atmospheric N deposition were obtained from the National Atmospheric Deposition Program[1] for monitoring stations in the vicinity of Fort Benning. Annual wet only N deposition (0.35 g N m^{-2} yr^{-1}) was converted to total N deposition using a factor of 2.0 that was derived from data collected in the southeastern US (Lovett and Lindberg, 1993). It was assumed that plant tissue C concentrations were 0.5 g C g^{-1} and plant tissue N concentrations were set to 1% based on data from different sources (Birk and Vitousek, 1986; Yin, 1993). Nitrogen concentrations in roots were assumed to be the same as those in foliage based on studies of loblolly pine on the upper Coastal Plain (Birk and Vitousek, 1986).

Table 4. Parameter values for variables in the excess N submodel

Variable	Abbreviation	Units	Value
Atmospheric N deposition	ATMN	g N m^{-2} yr^{-1}	0.7
Plant tissue N concentration	CONCN	%	1.0
Fraction of herbaceous plant N demand met through internal N translocation	HBTF	fraction	0.5
Fraction of tree N demand met through internal N translocation	WDYTF	fraction	0.5

Seasonal translocation of N in trees (Luxmoore et al., 1981; Ostman and Weaver, 1982) and herbaceous plants (Li et al., 1992) is a well known process. Its overall importance to plant nutrition is that under circumstances where soil N supplies limit plant growth, N demands for new tissue production are met through a redistribution of internal plant N. Studies of loblolly pine on sandy soils indicate that about 50% of the foliar N is translocated to wood prior to leaf senescence (Birk and Vitousek, 1986). Under conditions of low soil N availability, ≈50% of the N required for production of new biomass in herbaceous vegetation may be derived from internal N translocation (e.g., Li et al., 1992). Therefore, in the absence of site-specific information, the translocation factor was set at 50% for forest and herbaceous plant communities at Fort Benning.

[1] http://nadp.sws.uiuc.edu/

2.4 SENSITIVITY ANALYSIS

A sensitivity analysis was used to identify the parameters that had the greatest influence on model predictions. Measurement accuracy is most important for those parameters that have the greatest effect on model outputs. In addition, if variation in a parameter value does not alter model behavior, then steps to alter the process it represents might be of little use for promoting forest recovery and sustainability. Variance estimates are not well established for most parameters in the model. Therefore, the sensitivity analysis was performed by systematically varying each parameter in the model by ±20% of its base value, while holding all other parameters constant, and running the model to 100 years. The base value for NMINRATE and SOILC:N was set at 0.025 yr^{-1} and 20, respectively.

2.5 MODEL SCENARIOS

Both forest recovery and forest sustainability on less sandy and more sandy soils under different fire and timber management regimes was predicted with the model. Four performance variables (AGWB, SOC, SOILN, and PEN) were used to evaluate the predicted effects of harvesting and prescribed burning on forest recovery and sustainability. Two experiments were performed with the model. The first experiment tested the effect of prescribed burning and timber management on forest recovery from barren soils. The second experiment tested the effect of prescribed burning and timber management on forest sustainability following stand recovery from barren soils.

In the first experiment, forest recovery from barren soils was predicted for 100 years with or without prescribed burning and with or without forest management by thinning (50% REMOVAL) or clearcutting (99% REMOVAL). The time interval between harvests was fixed at 50 years. Each recovery scenario started with 300 g m^{-2} aboveground tree biomass, 350 g m^{-2} herbaceous aboveground biomass, and 630 g soil C m^{-2}. Data for the performance variables were recorded at the end of 100 years and model predictions were compared among the various scenarios. In experiment 1, less sandy soils (i.e., < 70% sand) and more sandy soils (i.e., > 70% sand) represented soils with "low N availability" and "high N availability", respectively.

In the second experiment, forest sustainability was predicted for a second 100 year cycle which followed 100 years of recovery in the absence of fire and timber management. In other words, after 100 years of forest growth, sustainability was predicted for a further 100 years either with or without prescribed burning and with or without forest management by thinning (50% REMOVAL) or clearcutting (100% REMOVAL). The time interval between harvests was fixed at 50 years. The initial conditions for aboveground tree biomass, herbaceous aboveground biomass, and soil C stocks were the same as in experiment 1. Data for the performance variables were recorded at the end of 200 years and the model predictions were compared among the various scenarios. As in experiment 1, less sandy soils (i.e., those with < 70% sand) and more sandy soils (i.e., those with > 70% sand) represented soils with "low N availability" and "high N availability", respectively. It is noted that these parameters are not necessarily those which Fort Benning forest managers are following or plan to follow in detail, but are believed to be representative of a realistic range of regionally observed practices.

3. RESULTS

3.1 SENSITIVITY ANALYSIS

The sensitivity analysis was used to examine the relative change in the four performance variables (AGWB, SOC, SOILN, and PEN) when each parameter value in the model was varied by ±20%. Predictions of aboveground tree biomass (AGWB) were most affected by a single parameter, maximum aboveground tree biomass (TARGET). A ±20% change in TARGET produced a proportional change in AGWB.

Predictions of soil C (SOC) were affected most by changes in SOCTT, fLEAF, TARGET, and LEAFTT. A ±20% change in each of the foregoing parameters produced a 5 to 20% change in predicted soil C stocks. Predictions of soil N (SOILN) were affected by the same set of parameters as predictions of SOC. However, the most important model parameter to predictions of soil N stocks was the soil C:N ratio (SOILC:N).

In order of relative importance, the most important parameters for prediction of PEN were SOILC:N, NMINRATE, SOCTT, CONCN, WDYTF, and LEAFTT. A ±20% change in each of the foregoing parameters produced more than a 20% change in predicted potential excess N (PEN). A 20% change in fLEAF, HBTF, TARGET, and ATMN produced a 5 to 20% change in predicted PEN. Potential excess N was a critical feedback on the recovery rate of aboveground tree biomass (AGWB), hence any change in parameters affecting PEN can be translated into changes in AGWB, soil C, and soil N.

3.2 FOREST RECOVERY FROM BARREN LAND

Predicted forest recovery from barren land on less sandy soils (with low N availability) with or without prescribed burning is illustrated in Figure 5. In the absence of prescribed fires, AGWB, SOC, SOILN, and PEN increased to steady state values in ≈100 years or less. At a fire return interval of 3 years, the recovery of AGWB was slowed because available soil N began to limit tree growth (i.e., PEN was intermittently > 0 and < 0). Predicted soil C and N stocks after 100 years were also substantially reduced with a fire return interval of 3 years. Increasing the fire return interval to 2 years, dramatically reduced predicted AGWB, SOC and SOILN, and indicated that PEN strongly limited forest recovery. The cause of the N limitation was the consumption of O-horizon C and N by prescribed fires.

Combined effects of prescribed burning and forest harvesting are summarized in Table 5.

Even with burning and harvesting together, predicted AGWB was > 90% of maximum aboveground tree biomass (i.e., TARGET) on soils with high soil N availability. On these latter soils, predicted C stocks ranged from 3256 to 3527 g C m^{-2} and predicted N stocks ranged from 93 to 101 g N m^{-2} (with a 3-year fire return interval). The predictions were within 25% of measured mean C stocks (3847 g C m^{-2}) and measured mean N stocks (118 g N m^{-2}) in more sandy soils at Fort Benning (Garten and Ashwood, 2004b).

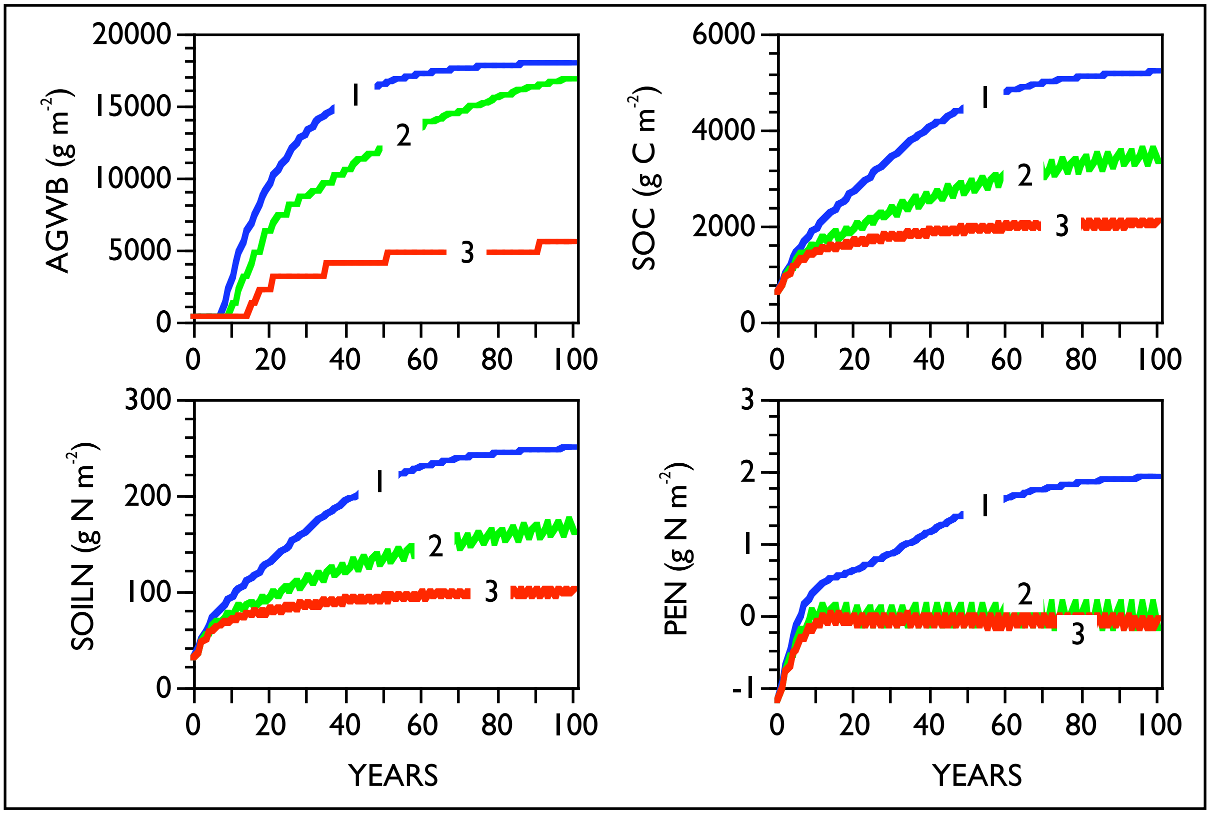

Fig. 5. Effect of prescribed burning on aboveground tree biomass (AGWB), soil C stocks (SOC), soil N stocks (SOILN), and potential excess N (PEN) on less sandy soils. Legend: (1) blue line = no fire; (2) green line = prescribed burn once every 3 years; (3) red line = prescribed burn once every 2 years.

Prescribed burning at 2- and 3-year intervals reduced predicted C and N stocks relative to the "no fire" scenario on soils with both low and high N availability (Table 5). On soils with low N availability, increased fire frequency had more effect on predicted forest recovery than stand thinning or clearcutting (50 year rotation). Prescribed burning at a 2- and 3-year return interval dramatically reduced predicted PEN which impacted predicted forest recovery. When burning occurred every other year, predicted aboveground tree biomass (AGWB) was reduced by ≈70%. On soils with low N availability, predicted C stocks ranged from 3089 to 3334 g C m^{-2} and predicted N stocks ranged from 147 to 159 g N m^{-2} (if the fire return interval was set to 3 years). The predictions were within 20% of measured mean C stocks (3709 g C m^{-2}) and measured mean N stocks (173 g N m^{-2}) in less sandy soils at Fort Benning (Garten and Ashwood, 2004b).

Table 5. Effect of harvesting (0, 50, or 99% removal of AGWB) and frequency of prescribed burning (FIREFREQ) on predicted recovery of aboveground forest biomass (AGWB, g m^{-2}), soil C stocks (SOC, g C m^{-2}), soil N stocks (SOILN, g N m^{-2}), and potential excess N (PEN, g N m^{-2}) on soils with low and high N availability (experiment 1). The time interval between thinning (50% removal) or clearcutting (99% removal) was 50 years. The predicted values were summarized following a 100 year model run.

REMOVAL %	FIREFREQ (years)	Low soil N availability				High soil N availability			
		AGWB	SOC	SOILN	PEN	AGWB	SOC	SOILN	PEN
0	No fire	17913	5210	248	1.91	17931	5221	149	5.00
	3	16861	3334	159	-0.19	17931	3527	101	1.90
	2	5439	2141	102	-0.04	17927	3336	95	1.56
50	No fire	17414	4982	237	1.76	17420	4987	142	4.71
	3	16125	3218	153	-0.19	17420	3390	97	1.79
	2	4769	2117	101	-0.00	17418	3213	92	1.47
99	No fire	16921	4755	226	1.61	16921	4757	136	4.42
	3	15183	3089	147	-0.19	16921	3256	93	1.68
	2	5258	2113	101	-0.04	16921	3093	88	1.38

3.3 FOREST SUSTAINABILITY

Predicted forest recovery from barren land and sustainability on less sandy soils (with low N availability) with timber management and without prescribed burning is illustrated in Figure 6. The timber management regime was stand thinning (50% removal of AGWB) on a 50 year rotation after the first 100 years of forest recovery. In the absence of prescribed fires, forest recovery was sustainable (i.e., predicted AGWB repeatedly returned to the maximum aboveground tree biomass following forest thinning). Predicted soil C and N stocks exhibited minor fluctuations that were related to changes in soil C inputs following tree removal.

Addition of a 3-year schedule of prescribed burning to the timber management regime did not seriously impact predicted AGWB even though predicted soil C and N stocks were dramatically reduced (Table 6). Prescribed burning caused predicted PEN to fluctuate near zero but there was enough N to allow recovery of predicted AGWB following forest thinning. When the fire frequency increased to once every 2 years, predicted AGWB declined after each stand thinning and predicted SOC, SOILN, and PEN declined over time (Fig. 6). The experiment indicated that some combinations of prescribed fire and timber management may preclude sustainable forest ecosystems on soils with low N availability. In particular, a schedule of prescribed burning once every 2 years plus forest thinning or clearcutting on a 50 year rotation could result in a failure of forest stands to recover to their maximum aboveground tree biomass.

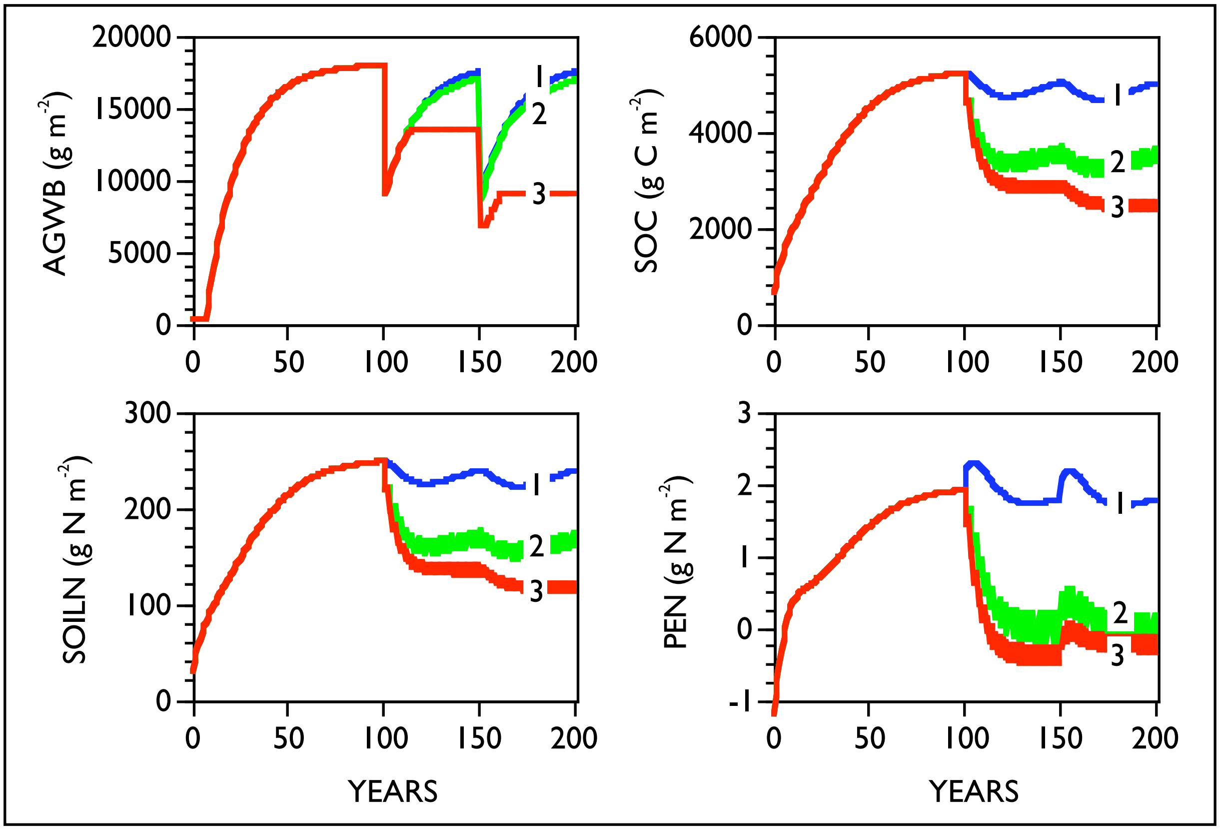

Fig. 6. Effect of prescribed burning and timber management (50% forest thinning at 100 and 150 years), following forest recovery, on aboveground tree biomass (AGWB), soil C stocks (SOC), soil N stocks (SOILN), and potential excess N (PEN) on less sandy soils. Legend: (1) blue line = no fire; (2) green line = prescribed burn once every 3 years, (3) red line = prescribed burn once every 2 years.

4. DISCUSSION

Prior research (Garten and Ashwood, 2004b) indicates there are four factors important to ecosystem recovery on degraded soils at Fort Benning: (1) initial amounts of aboveground biomass, (2) initial soil C stocks, (3) relative recovery rates of aboveground biomass, and (4) soil sand content. These same factors are also important in the current model-based analysis of the effects of prescribed fire and timber management on forest recovery and sustainability. Although other initial conditions are possible, recovery from barren soils was selected as the initial condition for both experiments with the model. The latter scenario represented an extreme type of ecosystem restoration that predicted high demands on soil N supplies by forest growth. Soil C and N stocks are greatly reduced in barren soils at Fort Benning which makes ecosystem recovery more difficult than when initial conditions for soil resemble those in less disturbed environments. The model indicates that if recovery rates are too high, forest growth was down regulated through feedbacks on potential excess N. Soil type and its relationship to soil N availability, as represented by less sandy and more sandy soils, was also a critical determinant of predicted forest recovery and sustainability under different regimes of prescribed burning and timber management.

Table 6. Effect of harvesting (0, 50, or 99% removal of AGWB) and frequency of prescribed burning (FIREFREQ) on predicted sustainability of aboveground forest biomass (AGWB, g m^{-2}), soil C stocks (SOC, g C m^{-2}), soil N stocks (SOILN, g N m^{-2}), and potential excess N (PEN, g N m^{-2}) on soils with low and high soil N availability (experiment 2). The time interval between thinning (50% removal) or clearcutting (99% removal) was 50 years. Treatments did not start until after 100 years of recovery and the predicted values were summarized after 200 years.

REMOVAL %	FIREFREQ (years)	Low soil N availability				High soil N availability			
		AGWB	SOC	SOILN	PEN	AGWB	SOC	SOILN	PEN
0	No fire	18000	5265	251	1.95	18000	5265	146	4.79
	3	17999	3549	169	-0.17	18000	3549	99	1.74
	2	17945	3352	160	-0.41	18000	3357	93	1.40
50	No fire	17438	5002	238	1.78	17438	5002	139	4.48
	3	16852	3500	167	0.01	17438	3397	94	1.62
	2	6003	2232	106	-0.04	17438	3220	89	1.31
99	No fire	16920	4759	227	1.62	16920	4759	132	4.18
	3	15464	3128	149	-0.19	16920	3631	90	1.51
	2	7301	2351	112	-0.08	16920	3094	86	1.22

The sensitivity analysis indicated that potential excess N, which was the contributing feedback from soil C and N dynamics to forest growth, was most sensitive to changes in soil C:N ratios and net soil N mineralization. Differences in these two soil properties were captured by considering two broad soil categories. More sandy soils (i.e., those with > 70% sand content) exhibit higher relative rates of net soil N mineralization than less sandy soils (i.e., those with < 70% sand content) at Fort Benning (Garten and Ashwood, 2004b). Even though soil N stocks are less on more sandy soils (due to their higher soil C:N ratios), more sandy soils have a higher estimated annual flux of net soil N mineralization than less sandy soils. The mineralization process contributed to increased levels of predicted PEN on more sandy soils (see Table 5). With a 3-year fire return interval, the predicted annual flux of net soil N mineralization in the model was ≈4 g N m^{-2} which is several times greater than *in situ* measurements of net soil N mineralization (0.5 to 1.2 g N m^{-2} yr^{-1}) under longleaf pine in southwestern Georgia (Wilson et al., 1999).

More sandy soils under perennial vegetation at Fort Benning have a significantly greater amount of soil C in particulate organic matter (Garten and Ashwood, 2004b) which is a highly labile C pool that is important to N availability, particularly in sandy soils (Hook and Burke, 2000; Willson et al., 2001). Greater amounts of labile soil organic matter may be one factor contributing to higher potential net soil N mineralization and elevated predictions of PEN in more sandy soils at Fort Benning. The sensitivity analysis indicated that model predictions could be further improved through more accurate measurements of net soil N mineralization and soil C:N ratios. As indicated above, *in situ*, site-specific measurements may provide different estimates of net soil N mineralization than the aerobic laboratory incubations on which NMINRATE was based for the purposes of the model. Several other variables also exerted an important control on PEN and thus potentially affect predictions of forest recovery and sustainability. Some, like plant tissue N concentrations, are more easily measured than others, like soil C turnover times and within plant N translocation.

Numerous studies (Neary et al., 1999; Wan et al., 2001) have examined the effects of prescribed burning on the sustainability of forest soil C and N reserves. Prescribed fires can substantially reduce O-horizon C and N stocks but they generally have no significant effect on mineral soil C and N. For example, Binkley et al. (1992) reported that the cumulative effects of 30 years of prescribed burning in Coastal Plain pine forests were generally limited to reduced C and N stocks in the forest floor. Prescribed burning may temporarily increase soil N availability and thereby promote establishment of herbaceous ground covers that can eventually stabilize burned areas. However, as the current model indicates, N losses from the forest floor as a consequence of prescribed fire may be significant to forest recovery when soils are nutrient poor and plant N demands are approximately in balance with soil N supply. Under such circumstances, prescribed fires may lower soil C and N stocks and create N deficiencies that limit forest recovery. By comparison, forest harvesting in the absence of prescribed burning had only a minor effect on soil C and N (Table 5). This result is similar to that from a model-based analysis of the effects of prescribed fire and forest harvesting on regrowth of Eucalyptus stands that indicated fire frequency had a greater effect on stand N balance than forest harvesting (McMurtrie and Dewar, 1997). Experiments with the current model also indicate that forest recovery and sustainability are more sensitive prescribed fire regimes than to forest thinning or clearcutting.

In summary, predictions of forest recovery and sustainability were directly influenced by how prescribed fire affected potential excess N or the difference between soil N supply and plant N demand. In the model, prescribed fire impacted soil N supplies by lowering soil C and N stocks which reduced the soil N pool that contributed to the predicted annual flux of net soil N mineralization. On soils with high soil N availability, increasing fire frequency in combination with stand thinning or clearcutting had little effect on predictions of forest recovery and sustainability. However, the model indicated that combined effects of stand thinning and frequent prescribed burning could have adverse effects on forest recovery and sustainability when soil N availability was just at the point of limiting forest growth. Model predictions indicated that prescribed burning with a 3-year return interval would decrease soil C and N stocks, but not adversely affect forest recovery from barren soils or forest sustainability following ecosystem recovery. On soils with low N availability, prescribed burning with a 2-

year return interval depressed predicted soil C and N stocks to the point where soil N deficiencies precluded forest recovery as well as forest sustainability following ecosystem recovery.

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