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forest management

Balancing Revenue and Nutrient Removals in *Pinus elliottii* Engelm. Stands Managed for Pinestraw and Wood Production

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The forest floor is an important component for long-term forest productivity and sustainability because it plays a central role in carbon and nutrient cycling. Raking the recently senesced pine foliage off the forest floor (pinestraw raking) has become a profitable economic activity in the southeastern United States, despite its potential negative effects on long-term soil fertility. We analyzed the impact of different pinestraw raking scenarios on the profitability and carbon (C) and nitrogen (N) balance of slash pine (*Pinus elliotti* Engelm. var. *elliottii*) forests. To analyze the tradeoffs between economic returns and nutrient removals, we defined an index of ecological and economic efficiency: economic nutrient removal efficiency (ENRE), calculated as the amount of economic return (as defined by land expectation value) per unit of nutrient removed. Nutrient removals and economic returns were lower for forest stands that were managed less intensively for pinestraw raking (i.e., raking from age 8 until age 15) compared with stands managed intensively for pinestraw raking (i.e., raking from age 8 until rotation age). However, the former option was more efficient in terms of minimizing C and N removals per unit of economic return generated. Management practices that lead to increased site productivity can accelerate stand development and shorten the time to begin raking, increasing the ENRE of pinestraw raking. Stands managed exclusively for pinestraw production (with higher planting density and shorter rotations and wood harvest being a secondary objective) showed 5–6 times lower ENRE than stands managed for traditional forestry, indicating much higher C and N removals for similar economic returns.

Keywords: slash pine, forest floor, pinestraw raking, sustainability, economic nutrient removal

Forest sustainability can be defined as the maintenance of the ecological integrity of forests, allowing them to provide environmental, social, and economic goods and services to meet the needs of people in perpetuity (Rempel et al. 2004). In slash pine (*Pinus elliotti* Engelm. var. *elliottii*) forests, without considering the mineral soil, the forest floor contains between 10 and 30% of total ecosystem carbon (C) (Gholz and Fisher 1982, Harding and Jokela 1994, Gonzalez-Benecke et al. 2010). Needlefall (NF) accounts for more than 75% of the total forest floor (Gonzalez-Benecke et al. 2010). The forest floor is an important component for maintaining long-term forest productivity and sustainability because it contributes to C and nutrient cycling (Pritchett and Fisher 1987, Aaltonen et al. 2011), provides habitat for diverse plant and animal species (Knapp et al. 2005), regulates the effects of climate on soil temperatures and moisture flow (Van Lear and Goebel 1976), and controls erosion (Gosz et al. 1976).

The Oi soil horizon is typically defined as the upper layer of the forest floor composed of recently senesced, relatively nondecomposed pine foliage. This "pinestraw" can be harvested and used for landscaping mulch in urban areas. Pinestraw mulch, typically from longleaf pine (*Pinus palustris* Mill.) and slash pine plantations, has become a lucrative initiative in the southeastern United States, generating around \$60–80 million annually to the economies of the states of Florida and Georgia (Casanova 2007). Factors such as increased population growth and improved economic conditions, particularly strong housing markets, favor the demand for pinestraw (Wolfe et al. 2005). Pinestraw raking may generate economic rents between \$173 and 247 ha^{-1} $year^{-1}$ for forest landowners (Minogue et al. 2007), although the current decline in the US demand for housing has led to lower demand and thus decreased prices for pinestraw. Pinestraw raking may also provide positive environmental externalities such as reduction in fuel loads and lowering the risk

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of wildfires (Pearson et al. 1995, Haywood et al. 1998, Clark and Saunders 2009, Haywood 2009).

Despite these economic and environmental benefits, raking pine needles from the Oi soil horizon has been associated with negative effects on C and nutrient balance, in some cases affecting long-term forest site productivity (Pritchett and Fisher 1987, Morris et al. 1992, Lopez-Zamora et al. 2001). In Europe, long-term litter removal from the 19th century until the 1950s reduced soil and foliar nutrient concentrations and caused declines in tree growth (Sayer 2006). Jandl et al. (2002) estimated a 50% reduction in tree growth for that period of time due to litter raking in the European Alps. Evidence from the United States has not been conclusive. Lunt (1951) and McLeod et al. (1979) reported growth losses in red pine (*Pinus resinosa* Ait.) and longleaf pine stands, respectively, after litter raking. Lopez-Zamora et al. (2001) found no impact on the growth of slash pine after 4 years of pinestraw raking. Likewise, Powers et al. (2005), Sanchez et al. (2006), and Zerpa et al. (2010) documented no negative effects on the growth of loblolly pine 10 years after the complete removal of the forest floor at the time of planting.

Other concerns associated with pinestraw raking are related to the negative impacts on the physical properties of the soil and changes in biodiversity resulting from intensive understory vegetation removal before initiation of pinestraw raking. Patterson et al. (2010) found that trafficking from raking and fertilization operations resulted in surface soil compaction in loblolly pine plantations. Kelly et al. (2000, 2002) and Kelly and Wentworth (2009) reported a decrease in species richness and composition and population densities of longleaf pine communities such as scrub oak, dry savanna, and mesic savanna after pinestraw raking. Ober and DeGroote (2011) found a decrease in the abundance of arthropods in loblolly pine stands after pinestraw raking, yet abundance was increased in longleaf and slash pine stands.

Previous studies have investigated the economic aspects of pinestraw raking in southern pine stands (Morris et al. 1992, Robertson 1992, Stainback and Alavalapati, 2004, Dickens et al. 2007a). Susaeta et al. (2012) found that the economic and nutrient removal effects of pinestraw raking were associated with the positive impacts of pinestraw management on the reduction of intensity and occurrence of wildfires. The model reported by Gonzalez-Benecke et al. (2012), which estimates NF dynamics in slash pine stands, was a useful tool that helps in understanding the interactions between stand development and NF fluxes, allowing quantifying C and nutrient removals associated with pinestraw raking.

In this article, we explored different economic, silvicultural, and ecological considerations of pinestraw raking in slash pine forests by extending the approach of Susaeta et al. (2012). Slash pine is a major commercial species, planted on more than 4.2 million ha in the southern United States, covering a wide range from eastern Texas to southern North Carolina to southcentral Florida (Barnett and Sheffield 2005). Our combined economic-ecological model allows quantifying C and nutrient removals as well as economic revenues associated with pinestraw raking. To address pinestraw raking sustainability, we include in our analysis an index of ecological and economic efficiency: the economic nutrient removal efficiency (ENRE) of pinestraw raking, defined as the ratio between economic return, as defined by land expectation value (LEV) ($\$ \text{ ha}^{-1}$), and removals of C or nitrogen (N; kg ha^{-1}).

Sustainable management of ecosystems requires that approaches be taken that maintain the productivity of those systems into the future. However, as discussed previously, scientific evidence about the long-term effects of raking the litter layer of the forest floor on the productivity of the forest is not conclusive. Nutrient removals associated with raking can be easily ameliorated through fertilizer application. On the other hand, it is less obvious how C removals with litter raking affect future productivity or even the accumulation of soil C, and amelioration of C removal is less straightforward than replacing lost mineral nutrients. In ecological situations, in which the future impact of current actions is unknown, the precautionary principle is often invoked, meaning basically that caution will be exercised in undertaking a new action when the future impacts of that action are not well known (Gollier and Treich 2003). There is active debate in the literature of how best to consider the precautionary principle within economic frameworks (e.g., Barker 2008, Aldred 2012). Economic justifications for the precautionary principle include capturing societal perception for the intrinsic value of environment and attitudes in light of risk and assuring future flexibility to capture new and unknown natural resource-based benefits (Emerton et al. 2005). In this article, we take a pragmatic approach to applying the precautionary principle, by examining the economic efficiency of nutrient removals (as defined above) under a range of forest management scenarios.

The objectives of this study were to examine the following questions about pinestraw raking in slash pine plantations: (1) What is the impact of different pinestraw raking management regimes on the profitability of the stand and C and N budgets?; (2) What are the effects of changes in site productivity and planting density on the economic rents and C and N balance due to pinestraw raking?; (3) Is there any interaction between site productivity and planting density on the initial age of raking?; (4) Are there any tradeoffs between stand productivity and forest floor C removal and the time needed to recover the C removed from the forest floor?; and (5) If stands are managed primarily for pinestraw raking rather than for traditional forestry with pinestraw raking as a secondary product objective, what are the ecological and economic implications?

Materials and Methods

Growth-and-Yield and Pinestraw Models

Stand growth-and-yield models for slash pine, reported by Pienaar et al. (1996) and modified to allow for multiple fertilizations (Bailey et al. 1999) and thinnings (Bailey et al. 1981, Pienaar 1995), were used to determine merchantable volume of forest products. Three forest product classes—sawtimber (st), chip-and-saw (cns), and pulpwood (pw)—were defined, depending on stem dbh (1.37 m) and merchantable diameter limits (Pienaar et al. 1996). The stem dbh and merchantable diameter (both outside bark) were, respectively, 29.2 and 17.8 cm for st, 19.1 and 15.2 cm for cns, and 11.4 and 7.6 cm for pw. Pinestraw production was determined using the model developed by Gonzalez-Benecke et al. (2012). In brief, yearly NF ($\text{Mg ha}^{-1}\text{ year}^{-1}$) was estimated as a function of stand density index (trees ha^{-1}) and site index (SI; m, at a reference age of 25 years). The stand density index for the previous year was correlated with the current year NF using a three-parameter sigmoidal function. Maximum yearly NF of the stand was found to be proportional to SI, a measure of site productivity (Gonzalez-Benecke et al. 2012). Yield per ha of pinestraw was converted to bales per ha, assuming 7.7 kg of pinestraw per bale and a raking efficiency conversion factor of 75% (Susaeta et al. 2012).

Needle dry mass in the forest floor (Mg ha^{-1}) was determined as the sum of yearly dry NF inputs corrected for decay losses using a decay rate of 15% year^{-1} (Gholz et al. 1985b, 1986, 1991, Binkley

Table 1. Description of different raking scenarios and silvicultural management systems used for slash pine.

Scenario	Period of raking (yr)	Raking frequency	Raking management: Weed control	Raking management: Fertilization
			(yr)	
Unthinned				
$R1_u$	8 until rotation age	Every other year	7,11,15,19	11,19
$R2_u$	8 until rotation age	Annually	7,11,15,19	11,19
$R3_u$	8 until yr 15	Every other year	7, 11	11
$R4_u$	8 until yr 15	Annually	7, 11	11
Thinned				
$R1_t$	8 until rotation age	Every other year until thinning; resume raking at yr 18 until rotation age	7,11,15,19	11,19
$R2_t$	8 until rotation age	Annually until thinning; resume raking at yr 18 until rotation age	7,11,15,19	11,19
$R3_t$	8 until yr 15	Every other year	7, 11	11
$R4_t$	8 until yr 15	Annually	7, 11	11

For all scenarios: bedding, weed control at planting and at year 1; fertilization (age 5) with 178 kg ha^{-1} diammonium phosphate; fertilization (age 15) with 140 kg ha^{-1} diammonium phosphate + 430 kg ha^{-1} urea. Raking scenarios: fertilization with 140 kg ha^{-1} diammonium phosphate + 430 kg ha^{-1} urea. Total nutrients added: N = 255 kg ha^{-1}, P = 146 kg ha^{-1} for B_u and B_t; N = 701 kg ha^{-1}, P = 275 kg ha^{-1} for R1 and R2; N = 478 kg ha^{-1}, P = 211 kg ha^{-1} for R3 and R4. Thinning: 33% removal of the standing basal area at age 15 years. Rotation length was not fixed, varying for each scenario depending on maximum LEV(t).

2002, Gonzalez-Benecke et al. 2010). C and N removals due to pinestraw raking were estimated using this model and C and N concentrations. The biomass of NF was transformed to C mass using an average C content of 50% (Clark et al. 1999, Smith et al. 2006). The average concentration of N in NF of slash pine was obtained from published values reported in the peer-reviewed literature, averaging 4.14 g kg^{-1} (Manis 1977, Burger 1979, Gholz et al. 1985a, Dalla-Tea and Jokela 1991). Net C and N removal due to pinestraw raking was determined after deducting, at rotation age, the biomass of needles in the forest floor with and without raking. Net C and N removals were not calculated by the amount of C and N in pinestraw bales taken from the site because there is inherent decay of the forest floor in situ. Therefore, at the end of the rotation, the amount of C and N remaining is less than the quantity removed at each raking.

Model of Timber and Pinestraw Benefits

The net present value of timber benefits PV_f was modeled as follows

$$PV_f = \exp^{-\delta t}\left[p_{st}\, v_{st}(t) + p_{cns}\, v_{cns}(t) + p_{pw}\, v_{pw}(t)\right] + \exp^{-\delta th} p_{th}\, v_{th} - \Sigma_0^t\, c_f(t) \exp^{\delta t} \quad (1)$$

where $v_{st}(t)$, $v_{cns}(t)$, and $v_{pw}(t)$ represent the merchantable volume of sawtimber, chip-and-saw, and pulpwood in m^3 ha^{-1} at time t (years), respectively, and v_{th} represents the volume of thinned material in m^3 ha^{-1} at fixed time t_h (years). Let v_{st}, p_{cns}, p_{pw}, and p_{th} denote the stumpage prices for sawtimber, chip-and-saw, pulpwood, and thinned material in US dollars m^{-3}, respectively, and let $\Sigma_0^t c_f(t)$ and δ denote the cumulative silvicultural costs associated with the establishment and development of the slash pine stand (\$ ha^{-1}) and real discount rate, respectively.

The net present value of pinestraw benefits PV_{ps} was modeled as follows

$$PV_{ps} = \left[\Sigma_{t_i}^t\, p_{ps}\, v_{ps}(t) \exp^{-\delta t} - \Sigma_{t_c}^t\, c_{ps}(t) \exp^{-\delta t}\right] \quad (2)$$

where $v_{ps}(t)$ and p_{ps} represent the number of bales per ha and price per bale (\$ bale^{-1}) at time t, respectively. The term $\Sigma_{t_i}^t p_{ps} v_{ps}(t)$ represents the cumulative economic returns due to pinestraw raking between initial time t_i and time t. The term $\Sigma_{t_c}^t c_{ps}(t)$ represents the cumulative costs associated with pinestraw raking production (\$ ha^{-1}) between initial time t_c and time t. The rationale for a different initial time for cost associated with pinestraw raking was that some silvicultural treatments are needed before commercial pinestraw raking production is started. This will be explained later in this section. If forestry use in perpetuity is assumed, the land expectation value LEV(t) can be expressed as

$$LEV(t) = \frac{PV_f + PV_{ps}}{1 - \exp^{-\delta t}} \quad (3)$$

From this equation, the optimal rotation age t^* was obtained by maximizing the LEV with respect to time t. In other words, rotation length was not fixed, varying for each scenario depending on maximum LEV(t). The effects of four different scenarios of pinestraw raking on LEV, PV_{ps}, and C and N removals were assessed by simulating stand growth and pinestraw yield for thinned and unthinned slash pine stands. In the case of the latter, p_{th} and v_{th} are set equal to zero in Equation 1.

Pinestraw Raking Scenarios

Table 1 shows, for thinned and unthinned slash pine stands, the different scenarios with their respective descriptions and silvicultural treatments. Two main factors were selected to define the scenarios: raking frequency (annual or every other year) and length of raking period (until age 15, first thinning or until rotation length). Pinestraw raking was set to start at age 8 years, after the onset of canopy closure. Initial parameters used were SI = 20 m and planting density (PD) = 1,500 trees ha^{-1}. The age of thinning was set at year 15 when applicable. Thinning intensity was set as 33% removal of the standing basal area (at age 15 years, the residual and removed BA were 25.1 and 8.2 m^2 ha^{-1}, respectively). We recognize that thinning age might depend on site quality and stand density. However, we decided to set the thinning age as constant to isolate the effect of length of raking period and simplify the analysis. Recall that, depending on the scenario, the accumulated economic rents due to pinestraw raking were obtained from age 8 years to age 15 years or optimal rotation age t^* years.

To address the second and third research questions, a sensitivity analysis was performed to determine the effects of site quality and

Table 2. Comparison of LEV, rotation age, number of rakings, PV_{ps}, C and N removals, and ENRE-C and ENRE-N for all management scenarios (SI = 20 m and PD = 750 trees ha^{-1}).

Scenario	LEV ($ ha^{-1})	RA (yr)	NR	PV_{ps} ($ ha^{81})	C (Mg ha^{-1})	N (kg ha^{-1})	ENRE-C	ENRE-N
							. . . . . .($ kg^{-1})	
$R1_u$	4,386	26	10	637	6.5	121.7	0.67	36.04
$R2_u$	6,091	26	19	1,739	12.0	232.5	0.51	26.20
$R3_u$	3,328	22	4	156	1.3	45.4	2.56	73.30
$R4_u$	4,283	22	8	715	2.9	92.1	1.48	46.50
$R1_t$	3,955	24	9	191	5.8	96.6	0.68	40.94
$R2_t$	5,146	24	17	926	10.5	182.3	0.49	28.23
$R3_t$	3,547	22	4	156	1.3	45.4	2.73	78.13
$R4_t$	4,501	22	8	715	2.9	92.1	1.55	48.87

R1, raking every other year from age 8 years until rotation age; R2, raking annually from age 8 years until rotation age; R3, raking every other year from age 8 years until age 15 years; R4, raking annually from age 8 years until age 15 years; u, unthinned; t, thinned (33% removal of the standing basal area at age 15 years). LEV included incomes from both pinestraw raking and timber harvest. PV_{ps} only included incomes from pinestraw raking. RA, rotation age; NR, number of rankings.

stand density on profitability of forestlands, NF dynamics, and C and N removals. The effect of site quality was assessed by evaluating the model under contrasting levels of intrinsic SI (14 versus 26 m), which approximated a wide range of site qualities observed in slash pine plantations in the southeastern United States. For this analysis, the difference in SI was not associated with differences in costs due to silviculture but rather to differences in native site characteristics. The effect of initial stand density was evaluated by running the model under contrasting PDs of 750 and 2,250 trees ha^{-1}. The economic indicators and C and N removals were compared with the original combination of SI and PD (i.e., SI = 20 m and PD = 1,500 trees ha^{-1}, respectively).

To answer our fourth research question, we estimated the time needed to recover the C removed from the forest floor using the model reported by Gonzalez-Benecke et al. (2010). We determined the total in situ (minus harvestable stem) C storage, assuming a rotation age of 24 years for slash pine (Dickens et al. 2007b) and an average net removal rate of 4 Mg ha^{-1} of C in the Oi layer of the forest floor. This value was calculated by averaging net C removals across all pinestraw raking and stand management scenarios shown in Tables 2 and 3. Total in situ (minus harvestable stem) C storage was computed as the sum of the net carbon accumulation in understory, forest floor plus coarse woody debris, and living pine biomass minus the carbon accumulated in the stemwood and bark, which is typically removed at harvest.

To address the sustainability of managing the stand primarily for pinestraw raking versus traditional forestry (with stemwood production as the primary product objective and pinestraw raking as a secondary product objective), we compared the land values and C and N removals of stands devoted primarily for pinestraw raking (pinestraw raking forestry [PSF]) versus stands managed under a traditional forestry (TF) scheme for sites with contrasting levels of SI. The PSF stand assumed yearly repeated raking from the age when pinestraw production was larger than 370 bales ha^{-1} to a fixed rotation age of 15 years and PD = 2,500 trees ha^{-1}. We brought forward the initial raking treatment to age 6 and 7 years for the PSF stands with SI = 26 and 20 m, respectively. For comparison purposes, we used a TF stand that included a raking management system consisting of annual raking from years 8 to 15, similar to the scheme $R3_u$ described in Table 1 with PD = 1,500 trees ha^{-1} and a rotation age of 24 years for unthinned slash pine plantations (Dickens et al. 2007b). For each silvicultural scheme, the removal of C was estimated as the difference in average C mass of needles in the forest floor (FF_{Needle}) against a nonraked stand over a 100-year period (6 rotations for PSF and 4 rotations for TF). Because there is no mechanistic model available for quantifying long-term N dynamics in the forest floor of slash pine stands, we determined the long-term N removals due to raking as the sum of all N content in pinestraw bales extracted over 100 years under both stand management scenarios.

The following costs associated with raking activities were assumed: chemical weed control cost of $136 ha^{-1} (Camron Owens, Rayonier Inc., pers. comm., Mar. 2, 2011), and fertilization cost of $170 ha^{-1} (Barlow and Dubois 2011). Furthermore, a cleanup cost of $173 ha^{-1} at year 17 was considered before the resumption of raking for the $R1_t$ and $R2_t$ scenarios (Dickens et al. 2007a). Based on Barlow and Dubois (2011), Fox et al. (2007), Peter et al. (2007), and Smidt et al. (2005), the following silvicultural management costs for all scenarios were assumed: a site preparation cost (shear, rake, pile, and bed) of $647 ha^{-1} and an aerial weed control cost before establishment of $163 ha^{-1}. Planting and seedling costs were assumed to be $0.085 $plant^{-1}$ and $0.05 $seedling^{-1}$, respectively. A banded weed control cost of $118 ha^{-1} and a fertilization cost of $ 170 ha^{-1} were incurred at year 1. Annual management costs were set at $20 ha^{-1}. A marking cost of $121 ha^{-1} was assumed for the thinned scenarios. (See Table 1 for further details on weed control and fertilization schedule and rates.)

The following average southeastern US stumpage prices were assumed: $31.2 m^{-3}, $19.1 m^{-3}, and $10.3 m^{-3} for st, cns, and pw, respectively (Timber Mart South 2010). The price of p_{ps} was set to $0.5 $bale^{-1}$. We also assumed a reduction in pinestraw yield of 50% after age 15 years for thinned scenarios. The rationale for this assumption is that the site may not have the same pinestraw yield because of fewer trees and increased understory competition that reduces the area to be raked (E.D. Dickens, School of Forestry and Natural Resources, University of Georgia, pers. comm., Feb. 27, 2011). A real discount rate of 4% was used in all economic analyses.

ENRE

We defined two ENRE ratios: economic C removal efficiency (ENRE-C, the ratio between LEV and net C removal, $ kg C^{-1}) and economic N removal efficiency (ENRE-N, the ratio between LEV and total N removal, $ kg N^{-1}).

Results and Discussion

Sustainable management of forest (and other) ecosystems usually involves management of risk under uncertainty: actions must be assessed with uncertain knowledge of the impacts of those actions on future productivity or ecosystem function. In this article, we propose the joint assessment of nutrient and C removals along with

Table 3. Comparison of LEV, PV_{ps}, C and N removals, and ENRE-C and ENRE-N for different SI and PD combinations for all raking scenarios with slash pine.

	PD = 1,500 (trees ha^{-1})												PD = 750 (trees ha^{-1})											
	SI = 14 m						SI = 26 m						SI = 20 m						SI = 20 m					
Scenario	LEV	PV_{ps}	C (Mg ha^{-1})	N (kg ha^{-1})	ENRE-C	ENRE-N	LEV	PV_{ps}	C (Mg ha^{-1})	N (kg ha^{-1})	ENRE-C	ENRE-N	LEV	PV_{ps}	C (Mg ha^{-1})	N (kg ha^{-1})	ENRE-C	ENRE-N	LEV	PV_{ps}	C (Mg ha^{-1})	N (kg ha^{-1})	ENRE-C	ENRE-N
	. .($ ha^{-1}). .				. . . .($ kg^{-1}). . . .		. . .($ ha^{-1}). .				. . . .($ kg^{-1}). . . .		. . .($ ha^{-1}). .				. . . .($ kg^{-1}). . . .		. . .($ ha^{-1}). .				. . . .($ kg^{-1}). . . .	
$R1_u$	501	198	4.1	77.6	0.12	6.46	10,503	980	8.7	150.3	1.21	69.88	4,538	401	6.1	97.5	0.74	46.54	4,073	584	6.4	111.6	0.64	36.50
$R2_u$	1,609	1,001	7.8	163.7	0.21	9.83	12,757	2,371	16	284.9	0.80	44.78	6,029	1,389	11.5	199	0.52	30.30	5,765	1,702	11.9	223.6	0.48	25.78
$R3_u$	−156	−53	0.7	28.5			9,165	385	2.2	63.7	4.17	143.88	3,502	26	1.1	35.6	3.18	98.34	3,157	184	1.6	47.4	1.97	66.60
$R4_u$	423	295	2.1	57.6	0.20	7.34	10,534	1,163	4.7	128.7	2.24	81.85	4,292	489	2.5	74.7	1.72	57.46	4,164	756	3.5	95.1	1.19	43.79
$R1_t$	265	-93	3.7	61.6	0.07	4.30	9,585	436	7.5	116.2	1.28	82.49	3,441	37	5.4	82.8	0.64	41.56	3,893	224	5.9	99.1	0.66	39.28
$R2_t$	1,024	403	6.9	123.9	0.15	8.26	11,246	1,448	13.9	233.8	0.81	48.10	4,451	611	9.3	145.8	0.48	30.53	5,111	976	10.6	186.2	0.48	27.45
$R3_t$	128	-53	0.8	28.5	0.16	4.49	9,009	385	2.2	63.7	4.10	141.43	3,204	26	1.1	35.6	2.91	90.00	3,485	184	1.4	47.4	2.49	73.52
$R4_t$	723	295	1.8	57.6	0.40	12.55	10,379	1,163	4.7	128.7	2.21	80.64	4,015	489	2.9	74.7	1.38	53.75	4,472	756	3.5	95.1	1.28	47.02

R1, raking every other year from age 8 years until rotation age; R2, raking annually from age 8 years until rotation age; R3, raking every other year from age 8 years until age 15 years; R4, raking annually from age 8 years until age 15 years; u, unthinned; t, thinned (33% removal of the standing basal area at age 15 yr). LEV included incomes from both pinestraw raking and timber harvest. PV_{ps} only included incomes from pinestraw raking.

revenues as a possible approach for the management of pinestraw raking, given uncertainty about the future effects of those nutrient removals. Specifically, we put forward ENRE (the net revenues per unit nutrient removal) as one possible index useful for applying the precautionary principle to the management of pinestraw raking in southeastern US forests.

Economic Indicators and C and N Removals

The LEVs, PV_{ps}, number of rakings, C and N removals, and ENRE-C and ENRE-N for all scenarios are presented in Table 2. For slash stands with SI = 20 m and PD = 1,500 trees ha^{-1}, higher LEVs were obtained with the inclusion of pinestraw raking into traditional forest management regimes, mainly associated with unthinned stands raked yearly until rotation age ($R2_u$). These results were expected because unthinned scenarios had greater rates of NF and longer rotation ages than thinned scenarios. On the other hand, raking until age 15 years would be more efficient in terms of nutrient removals and economic indicators than the annual pinestraw raking option. For example, when unthinned stands with SI = 20 m and PD = 1,500 trees ha^{-1}were raked annually up to age 15 years ($R4_u$), ENRE-C and ENRE-N were 1.48 and 46.50 \$ kg^{-1}, respectively. When the same stands were raked annually until rotation age ($R2_u$), ENRE-C and ENRE-N were 0.51 and 26.20 \$ kg^{-1}, respectively. The optimal rotation age for all the annual raking scenarios was always longer than the optimal rotation age for the every-other-year raking scenarios. Furthermore, the rotation ages for all raking scenarios were longer than those for the nonraked scenarios.

Higher C and N removals were found in those scenarios when annual raking was coupled with extended rotation ages. Across thinning regimes, on average, removals of C and N were 4.1 and 2.3 times greater for stands raked until the end of the rotation and 1.9 times greater for stands raked annually. Forest managers might also be encouraged to undertake the rake every-other-year until age 15 years then thin management scenario, as reflected by a relatively similar LEVs, increased PV_{ps}, and shorter rotation age for the $R3_t$ versus $R1_t$ scenario. Across raking scenarios, the average N removal for each pinestraw harvest was between 11 and 12 kg ha^{-1}, for both, unthinned or thinned stands.

Sensitivity Analysis

The effects of SI and PD on profitability and C and N removals for the different pinestraw raking scenarios are shown in Table 3. With all other parameters held constant, site quality (or potential productivity) reflected by SI was the major driver of profitability and C and N removals. Consistent with expectations, higher economic indicators were obtained with greater SI. Likewise, higher removals of C and N were also associated with pinestraw raking on higher quality sites. Modifying PD had a minor impact on land value. Decreased PD implied lower removals for both C and N.

Regardless of the combination of SI and PD, net C and N removals were always greater for the annually raked scenarios (Table 3). The effect of raking period length was even greater: 3.7 times larger C removal in stands raked until the end of the rotation (Table 3). This response can be explained by the accumulation of the forest floor between raking events in the every-other-year scenarios and, principally, by the accumulation of forest floor between age 15 years (when raking ended) and the end of the rotation. Susaeta et al. (2012) reported that, at rotation age, there were no differences in total C in the needles of the forest floor between stands nonraked and stands raked until age 15 years. On the other hand, stands raked

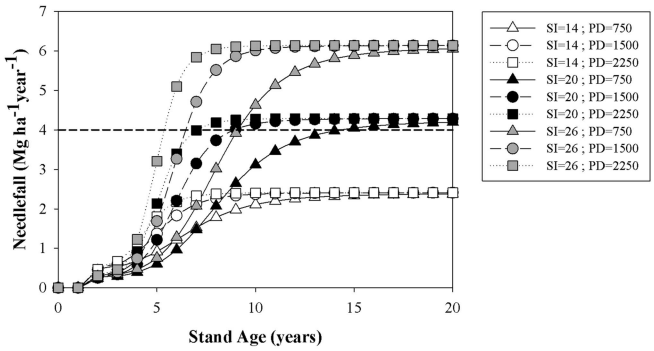

Figure 1. Effect of SI (m) and PD (trees ha^{-1}) on NF production in slash pine stands. Dashed line indicates a threshold value of 370 bales ha^{-1} (~4 Mg ha^{-1}) for pinestraw harvest.

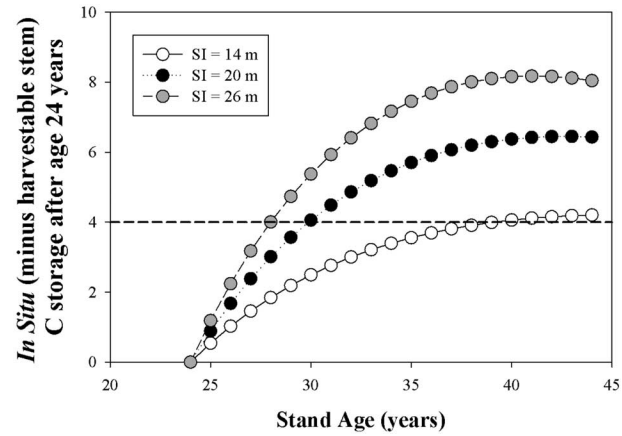

Figure 2. Time series of total in situ (minus harvestable stem) C storage in slash pine stands having different levels of SI (m) over a 24-year rotation.

until rotation length had 41% less forest floor mass. The same authors reported reductions in forest floor mass of 33 and 7% when stands were raked annually and every other year, respectively.

Higher ENRE was found with increased SI (Table 3). For example, across thinning regimes and pinestraw raking scenarios, for SI = 14, 20 and 26 m, ENRE-C ratios were 0.15, 0.88, and 1.45 \$ kg^{-1}, respectively. In the case of ENRE-N, the ratios were 6.67, 41.67 and 71.43 \$ kg^{-1}, respectively. Planting density had a minor effect on ENRE-C and ENRE-N: about 9 and 16% higher efficiencies were found in stands with PD = 750 trees ha^{-1} compared with stands with PD = 2,250 trees ha^{-1}, respectively.

Susaeta et al. (2012) pointed out that slash pine stands planted on more productive sites would have lower net C removal per unit economic revenue. Figure 1 shows the relationship between NF production and stand age when a minimum number of pinestraw bales (370 bales ha^{-1}, ~4 Mg ha^{-1}) could be achieved as a starting point value for contractors to begin raking in slash pine stands (David Dickens, Warnell School of Forestry and Natural Resources, University of Georgia, pers. comm., Feb. 27, 2011). NF accumulation could not reach the starting point value at any age for a SI = 14 m. The initial age of raking would start earlier in stands with a higher SI. In addition, for the same SI, the initial age of raking would start earlier for stands with higher PD. For example, for stands with SI = 26 m, the initial age of raking would be around 6 years for PD = 2,250 trees ha^{-1} or at age 9 years if the stand was planted with 750 trees ha^{-1}. If the stand had a SI = 20 m, the initial age of raking would begin at age 7 or 13 years if the stand was planted with 2,250 or 750 trees ha^{-1}, respectively. Increasing site productivity and stand density may accelerate stand development, shorten the time to begin raking, and increase raking yields and financial returns. Silvicultural activities such as fertilization and weed control and the use of genetically enhanced seedlings should be encouraged to increase the productivity of the site (Jokela et al. 2010).

Analysis of C and N Removals and Site Productivity

Despite the fact that increasing intensity of pinestraw raking may cause greater C and nutrient removals, there is no definitive information regarding C and nutrient removal thresholds beyond which site quality would be impaired. This lack of information prevents the determination of optimal removal levels for long-term forest soil sustainability. A potential economic estimation approach to this problem is to explore the marginal cost of C in terms of LEVs and assume as thresholds those removal values that result in constant marginal LEVs. We considered a maximum marginal cost of C removal as 1% of the average LEVs obtained for stands using all levels of SI tested (Tables 2 and 3; marginal LEV). Thus, the threshold values of C removals occurred when the difference in LEVs between two consecutive periods (marginal LEV) was less than the 1% of the average LEVs. The threshold values of C were 11.6 Mg ha^{-1} for stands with SI = 14 m, 4.5 Mg ha^{-1} for stands with SI = 20 m, and 4 Mg ha^{-1} for stands with SI = 26 m.

We also examined tradeoffs between stand productivity and forest floor C removal. Because there is no available information for the effects of removal of slash pine on the forest floor on stand productivity, we used data from a residue removal experiment in 15-year-old *Pinus radiata* (Jones et al. 2011, Oliver et al. 2011), a related species member of the subsection *Australes* of the *Pinus* genus (southern pines). From this experiment, we derived an average growth loss ratio of 0.51 Mg ha^{-1} of stemwood C for each 1 Mg ha^{-1} of forest floor C at planting. We considered this ratio and C storage of 60 and 33.5 Mg ha^{-1} in stemwood of slash pine stands for SI = 26 m and SI = 22 m at age 26 years, respectively (Vogel et al. 2011). By taking this value and assuming a 5% loss in C stemwood growth on each site, it would be equivalent to removing 6 and 3.2 Mg ha^{-1} of C from the forest floor, respectively.

To recover 4 Mg ha^{-1} of C removed by pinestraw raking from the forest floor, average net C removal reported in Tables 2 and 3, it would be necessary to lengthen the rotation age by 15, 6, and 4 years for stands with SI = 14 m, SI = 20 m, and SI = 26 m, respectively (Figure 2). After this period, the stand would accumulate into the in situ C pool (minus harvestable stem) the same level of biomass that was removed by pinestraw raking.

TF Versus PSF

An important decision for forest managers and landowners is to determine whether to devote forest stand management primarily for PSF or TF with pinestraw raking as a secondary product objective. Table 4 shows the LEV and C and N economic removals efficiency for PSF and TF stands with different SIs. On highly productive sites (e.g., SI = 26 m), PSF managed stands yielded a 2% lower LEV than TF managed stands. Nevertheless, the pinestraw-oriented strategy reduced by 14% the profitability of the stand when SI = 20 m (Table 4). Even though our evidence suggested that similar returns can be obtained with shorter rotation ages when slash pine stands are managed primarily for pinestraw raking, higher removal rates of C

Table 4. Comparison of LEV, C and N removals due to raking, and ENRE-C and ENRE-N between PSF and TF for unthinned slash pine stands having different levels of SI after 100 years of continuous management.

	PSF					TF				
SI	LEV ($ ha^{-1})	C (Mg ha^{-1})	N (kg ha^{-1})	ENRE-C	ENRE-N	LEV ($ ha^{-1})	C (Mg ha^{-1})	N (kg ha^{-1})	ENRE-C	ENRE-N
				. . . . .($ kg^{-1})					. . . . .($ kg^{-1})	
20 m	3,590	51.4	873.4	69.86	4.11	4,180	8.2	526.2	512.25	7.94
26 m	9,945	75.5	1,342.7	131.69	7.41	10,150	12.6	735.2	803.64	13.81

Long-term C removal due to raking was estimated as the difference in mean C stock in needles in forest floor for raked and nonraked scenarios during 100 years. Long-term N removals due to raking were determined as the sum of all N content in pinestraw bales extracted during 100 years. LEV was calculated assuming forestry use in perpetuity and included incomes from both pinestraw raking and timber harvest.

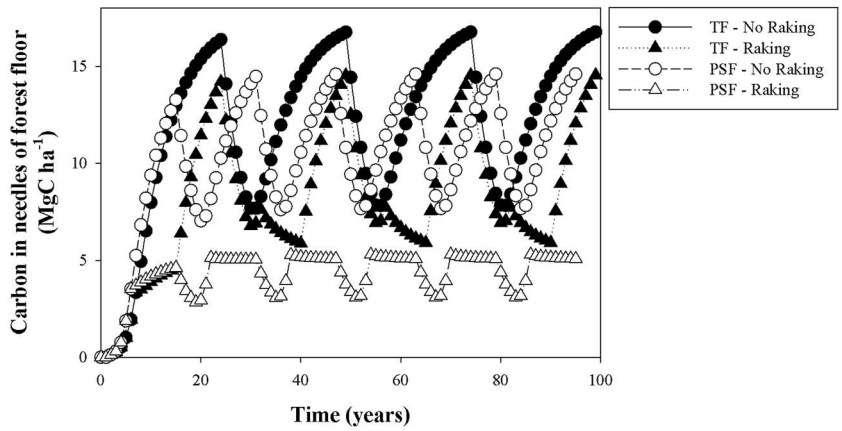

Figure 3. Carbon stock in needles of the forest floor for raked and nonraked slash pine plantations (SI = 20 m) under PSF and TF schemes for a 100-year period.

were also a consequence of the more intensive pinestraw raking schemes.

After 100 years of continuing the same stand management, lower ENRE was found if slash pine stands were managed using PSF. For example, in stands with SI = 20 m, C_{eff} of TF was about 6.3 times larger than that of PSF. That lower level of ENRE was explained by the fact that the net C removals were 5.1 times larger and the revenues were 14% lower than for TF (Table 4). Similar results were found for SI = 26 m, but the difference in ENRE was about 6.1 times larger for TF. As was stated previously in the sensitivity analysis section, higher ENRE was found with increased SI. In the case of N, TF had about double N_{eff} than PSF. These results indicate the lack of sustainability of PSF management: larger long-term C and N loss with no larger revenues.

The amounts of N removal presented in Table 4 represent between 11 and 29% of the total N contained in the surface 1 m of soil (Harding and Jokela 1994: 5550 kg N ha^{-1}, Vogel et al. 2011: 3557 kg N ha^{-1}). Although this removal of N may be considered significant, it is doubtful whether the forest floor can be considered a source of N (Piatek and Allen 2001).

An example of the dynamics of needle mass in forest floor (FF_{Needle}) for the PSF and TF schemes is presented in Figure 3. It was assumed that after a clearcut harvest, no burning of the residues had occurred and the efficiency of pinestraw raking was 75%. The nonraked TF stand reached a maximum C stock in the FF_{Needle} of 16.8 Mg ha^{-1} of C at a rotation age of 24 years. Under the PSF regime (annual raking from age 8 until age 15 years), the same stand had a C stock of 14.5 Mg ha^{-1} in FF_{Needle} at the same rotation age. In the case of plantations oriented toward pinestraw production (PSF) with a rotation age of 15 years, the nonraked and raked stands reached 14.6 and 5.16 Mg ha^{-1} of C in FF_{Needle}, respectively. The 9-year period without pinestraw raking (between 16 and 24 years) permitted the stands with TF to recover the forest floor mass and thereby reduce, at least partially, the negative impacts of pinestraw removals. In the case of stands with PSF, the constant extraction of pinestraw without a recovery period produced the largest decline in FF. It is also important to mention that, besides soil fertility, pinestraw harvesting can affect other soil physical properties, such as susceptibility to erosion and compaction (Morris et al. 1992). Another potential detrimental effect of pinestraw raking, associated with the weed control needed to prepare the stand for raking, could be a reduction in forest floor and soil C and N pools. Vogel et al. (2011) reported, for a 26-year-old slash pine stand, that sustained understory weed control from planting increased C accumulation in pine trees but decreased forest floor and soil C pools, resulting in no gain in ecosystem C. Sustained fertilization, on the other hand, increased the forest floor, soil, and tree C pools. Those potential effects are not directly addressed by this study and could also affect the suitability for pinestraw harvesting.

Conclusions

Unlike previous studies, we combined a biometric model to estimate NF (and therefore pinestraw production) with a standard economic model to quantify the ENRE under different pinestraw raking scenarios. We assessed ENRE, defined as net revenues per unit removal, as a possible indicator for assessing application of the precautionary principle in management of forest ecosystems.

The conclusions from our study can be summarized as follows:

- Greater economic returns would be obtained if forestlands were annually raked until rotation age and for landowners such as real estate investment trusts, maximization of profits from pinestraw harvesting might be the best choice until the property is sold. However, if long-term ownership is planned, greater C and N removals were also found in those stands, particularly when raking was performed on high-quality sites.
- Slash pine stands may also be annually raked for a shorter period of time (until age 15 years), given that annually raked stands may generate similar and earlier economic returns than stands raked every other year until rotation age and potentially be more efficient in terms of nutrient removals per economic revenue. For example, for $1 of net income due to raking, continued pinestraw harvests up to the rotation age would imply 150% greater removal of C compared with pinestraw raking up to age 15 years.
- Regardless of the horizon planning, forest managers should also consider planting or managing their most highly productive sites, in terms of economic sustainability and as a way to increase the land's value of the forest, with high raking intensities, because nutrient removals would be lower per unit economic revenue.
- Although evidence for the detrimental effects of pinestraw raking on long-term forest stand productivity are not conclusive in the southern United States, the precautionary principle suggests that the addition of fertilizers may, in part, mitigate negative potential impacts. This management practice may also shorten the time to begin raking and increase economic revenues due to improved site productivity. Furthermore, lengthening the rotation age, particularly for low productivity sites, may represent another option to offset C removals in the forest floor due to pinestraw raking.
- The sustainability of devoting forestlands primarily for a pinestraw management objective remains doubtful. Although similar and earlier economic returns would be realized compared with those for traditional forestry objectives, the ENRE was five to six times lower than that for traditional forestry.

Future researchers should focus on exploring the impacts of forest floor removal on soil physical and chemical properties as well as long-term site productivity. Analysis of future pinestraw and land markets is also a subject for further economic research.

Literature Cited

AALTONEN, H., J. PUMPANEN, M. PIHLATIE, H. HAKOLA, H. HELLEN, L. KULMALA, T. VESALA, AND J. BÄCK. 2011. Boreal pine forest floor biogenic volatile organic compound emissions peak in early summer and autumn. *Agr. For. Meteorol.* 151:682–691.

ALDRED, J. 2012. Climate change uncertainty, irreversibility and the precautionary principle. *Cambridge J. Econ.* 36:1051–1072.

BAILEY, R.L., N.C. ABERNETHY, AND E.P. JONES. 1981. Diameter distributions models for repeatedly thinned slash pine plantations. P. 115–126 in *Proc. of the 1st Biennial southern silvicultural research conference, Atlanta, GA, 6–7 November 1980*, Barnett, J.P. (ed.). USDA For. Serv., Gen. Tech. Rep. SO-34, New Orleans, LA.

BAILEY, R.L., S.W. MARTIN, AND E.J. JOKELA. 1999. Growth and yield predictions for lower Coastal Plain slash pine plantations fertilized at mid-rotation. *South. J. Appl. For.* 23:39–45.

BARKER, T. 2008. The economics of avoiding dangerous climate change. An editorial essay on The Stern Review. *Climate Change* 89: 173–194.

BARLOW, R.J., AND M.R. DUBOIS. 2011. Cost and cost trends for forestry practices in the South. *For. Land. Mag.* 6:16–24, 2011.

BARNETT, J.P., AND R.M. SHEFFIELD. 2005. Slash pine: Characteristics, history, status and trends. P. 1–6 in *Proc. of the Slash pine symposium: Slash pine: Still growing and growing!, Jekyll Island, GA, 23–25 April 2002*, Dickens, E.D., J.P. Barnett, W.G. Hubbard, and E.J. Jokela (eds.). USDA For. Serv., Gen. Tech. Rep. SRS-76, Ashville, NC.

BINKLEY, D. 2002. Ten-year decomposition in a loblolly pine forest. *Can. J. For. Res.* 32:2231–2235.

BURGER, J.A. 1979. *The effects of harvest and site preparation on the nutrient budget of an intensively managed southern pine forest ecosystem.* PhD thesis, University of Florida, Gainesville, FL. 370 p.

CASANOVA, V. 2007. *Three essays on the pine straw industry in a Georgia community.* PhD thesis, Auburn University, Auburn, AL. 113 p.

CLARK, K.L., H.L. GHOLZ, J.B. MONCRIEFF, F. CROPLEY, AND H.W. LOESCHER. 1999. Environmental controls over net exchanges of carbon dioxide from contrasting Florida ecosystems. *Ecol. Appl.* 9:936–947.

CLARK, N.A., AND B.P. SAUNDERS. 2009. The role of longleaf pine in the conservation framework of the southeast United States. P. 49–57 in *Proc. of the 31st Southern conservation agricultural systems conference: A multidisciplinary approach to conservation, Melfa, VA, 20–23 July 2009*, Reiter, M.S. (ed.). Polytechnic Institute and State University, Department of Crop and Soil Environmental Science, Eastern Shore Agricultural Research Extension Center Extension Publ. 2910−1417, Painter, VA.

DALLA-TEA, F., AND E.J. JOKELA. 1991. Needlefall, canopy light interception and productivity of young intensively managed slash and loblolly pine stands. *For. Sci.* 37:1298–1313.

DICKENS, E.D., C.W. DANGERFIELD, AND D.J. MOORHEAD. 2007a. *Economics of growing slash and loblolly pine on a 33-year rotation with and without thinning, fertilization, and pine straw–Annual equivalent value and soil expectation value.* University of Georgia, Warnell School of Forestry and Natural Resources, Series Pap. 5, Athens, GA. 15 p.

DICKENS, E.D., C.W. DANGERFIELD, AND D.J. MOORHEAD. 2007b. *Economics of growing slash and loblolly pine to a 24-year rotation with and without thinning, fertilization, and pine straw–Net revenue and rate of return.* University of Georgia, Warnell School of Forestry and Natural Resources, Series Pap. 1, Athens, GA. 14 p.

EMERTON, L., M. GRIEG-GRAN, M. KALLESOE, AND J. MACGREGOR. 2005. Economics, the precautionary principle and natural resource management: Key issues, tools and practices. P. 253–274 in *Biodiversity and the precautionary principle: Risk and uncertainty in conservation and sustainable use*, Cooney, R., and B. Dickson (eds.). Earthscan, Sterling, VA.

FOX, T.R., H.L. ALLEN, T.J. ALBAUGH, R. RUBILAR, AND C.A. CARLSON. 2007. Tree nutrition and forest fertilization of pine plantations in the southern United States. *South. J. Appl. For.* 31:5–11.

GHOLZ, H.L., AND R.F. FISHER. 1982. Organic matter production and distribution in slash pine (*Pinus elliottii*) plantations. *Ecology* 63:1827-1839.

GHOLZ, H.L., R.F. FISHER, AND W.L. PRITCHETT. 1985a. Nutrient dynamics in slash pine plantation ecosystems. *Ecology* 66:647–659.

GHOLZ, H.L., C.S. PERRY, W.P. CROPPER JR., AND L.C. HENDRY. 1985b. Litterfall, decomposition and N and P immobilization in a chronosequence of slash pine (*Pinus elliottii*) plantations. *For. Sci.* 31:463–478.

GHOLZ, H.L., L.C. HENDRY, AND W.P. CROPPER JR. 1986. Organic matter dynamics of fine roots in plantations of slash pine (*Pinus elliottii*) in north Florida. *Can. J. For. Res.* 16:529–538.

GHOLZ, H.L., L.M. KRAZYNSKI, AND B.G. VOLK. 1991. Disappearance and compressibility of buried pine wood in a warm temperate soil environment. *Ecol. Appl.* 1:85–88.

GOLLIER, C., AND N. TREICH. 2003. Decision-making under scientific

uncertainty: The economics of the precautionary principle. *J. Risk Uncert.* 27: 77–103.

GONZALEZ-BENECKE, C.A., E.J. JOKELA, AND T.A. MARTIN. 2012. Modeling the effects of stand development, site quality, and silviculture on leaf area index, litterfall, and forest floor accumulations in loblolly and slash pine plantations. *For. Sci.* 58:457–471.

GONZALEZ-BENECKE, C.A., T.A. MARTIN, W.P. CROPPER JR., AND R. BRACHO. 2010. Forest management effects on in situ and ex situ slash pine forest carbon balance. *For. Ecol. Manage.* 260: 795–805.

GOSZ, J.R., G.E. LIKENS, AND F.H. BORMANN. 1976. Organic matter and nutrient dynamics of the forest and forest floor in the Hubbard Brook forest. *Oecologia* 22:305–320.

HARDING, R., AND E.J. JOKELA. 1994. Long-term effects of forest fertilization on site organic matter and nutrients. *Soil Sci. Soc. Am. J.* 58:216–221.

HAYWOOD, J.D., A.E. TIARKS, M.L. ELLIOTT-SMITH, AND H.A. PEARSON. 1998. Response of direct seeded *Pinus palustris* and herbaceous vegetation to fertilization, burning, and pine straw harvesting. *Biomass Bioenergy* 14:157–167.

HAYWOOD, J.D. 2009. Influence of pine straw harvesting, prescribed fire, and fertilization on a Louisiana longleaf pine site. *South. J. Appl. For.* 33(3):115–120.

JANDL, R., F. STARLINGER, M. ENGLISCH, E. HERZBERGER, AND E. JOHANN. 2002. Long-term effects of a forest amelioration experiment. *Can. J. For. Res.* 32:120–128.

JOKELA, E.J., T.A. MARTIN, AND J.G. VOGEL. 2010. Twenty-five years of intensive forest management with southern pines: Important lessons learned. *J. For.* 108:338–347.

JONES, H.S., P.N. BEETS, M.O. KIMBERLEY, AND L.G. GARRETT. 2011. Harvest residue management and fertilisation effects on soil carbon and nitrogen in a 15-year-old *Pinus radiata* plantation forest. *For. Ecol. Manage.* 262:339–347.

KELLY, L.A., T.R. WENTWORTH, AND C. BROWNIE. 2000. Short-term effects of pine straw raking on plant species richness and composition of longleaf pine. *For. Ecol. Manage.* 127:233–247.

KELLY, L.A., T.R. WENTWORTH, AND C. BROWNIE. 2002. Scaling species dynamics in *Pinus palustris* communities: Effects of pine straw raking. *J. Veg. Sci.* 13:755–764.

KELLY, L.A., AND T.R. WENTWORTH. 2009. Effects of mechanized pine straw raking on population densities of longleaf pine seedlings. *For. Ecol. Manage.* 259:1–7.

KNAPP, E.E., J.E. KEELEY, E.A. BALLENGER, AND T.J. BRENNAN. 2005. Fuel reduction and coarse woody debris dynamics with early season and late season prescribed fire in a Sierra Nevada mixed conifer forest. *For. Ecol. Manage.* 2008:383–397.

LOPEZ-ZAMORA, I., M.L. DURYEA, C. MCCORMAC-WILD, N.B. COMERFORD, AND D.G. NEARY. 2001. Effect of pine needle removal and fertilization on tree growth and soil P availability in a *Pinus elliottii* Engelm. var. e*lliottii* stand. *For. Ecol. Manage.* 148:125–134.

LUNT, H.J. 1951. Liming and twenty years of litter raking and burning under red (and white) pine. *Soil Sci. Soc. Am. J.* 15:381–390.

MANIS, S.V. 1977. *Biomass and nutrient distribution within plantations and natural slash pine stands on wet coastal sites*. PhD thesis, University of Florida, Gainesville, FL. 142 p.

MCLEOD, K.W., C. SHERROD, AND T.E. PORCH. 1979. Response of longleaf pine plantations to litter removal. *For. Ecol. Manage.* 2:1–12.

MINOGUE, P.J., H.K. OBER, AND S. ROSENTHAL. 2007. *Overview of pine straw production in north Florida: Potential revenues, fertilization practices, and vegetation management recommendations.* University of Florida, School of Forest Resources and Conservation, Series FOR 125, Gainesville, FL. 6 p.

MORRIS, L.A., E.J. JOKELA, AND J.B. O'CONNOR. 1992. *Silvicultural guidelines for pinestraw management in the southeastern United States.* Georgia Forest Res. Pap. 88, Georgia Forestry Commission, Athens, GA. 11 p.

OBER, H.K., AND L.W. DEGROOTE. 2011. Effects of litter removal on arthropod communities in pine plantations. *Biodivers. Cons.* 20:1273-1286.

OLIVER, G.R., P.N. BEETS, S.H. PEARCE, J.D. GRAHAM, AND L.G. GARRETT. 2011. Carbon accumulation in two *Pinus radiata* stands in the North Island of New Zealand. *N.Z. J. For. Sci.* 41:71–86.

PATTERSON, W.B., M.A. BLAZIER, AND S.L. HOTARD. 2010. Pinestraw raking, fertilization and poultry litter amendment effects on soil physical properties for a mid-rotation loblolly pine plantation. P. 43–46 in *Proc. of the 14th Biennial Southern Silvicultural Research Conference, Athens, GA, 26–1 February/March 2007*, Stanturf, J.A. (ed.). USDA For. Serv., Gen. Tech. Rep. SRS-121, Asheville, NC.

PEARSON, H.A., R.L. KNOWLES, P.G. MIDDLEMISS, V.C. BALDWIN, AND R.L. BUSBY. 1995. United States agroforestry estate model. *Compiler* 13:27–37.

PETER, G.F., D.E. WHITE, R. DE LA TORRE, R. SINGH, AND D. NEWMAN. 2007. The value of forest biotechnology: A cost modelling study with loblolly pine and kraft linerboard in the southeastern USA. *Int. J. Biotech.* 9:415–435.

PIATEK, K., AND H.L. ALLEN. 2001. Are forest floors in mid-rotation stands of loblolly pine (*Pinus taeda*) a sink for nitrogen and phosphorus? *Can. J. For. Res.* 31:1164–1174.

PIENAAR, L.V. 1995. *Results and analysis of a slash pine spacing and thinning study in the southeastern Coastal Plain.* University of Georgia, Warnell School of Forestry and Natural Resources, Plantation Management Research Cooperative Tech. Rep. 1995-3, Athens, GA.

PIENAAR, L.V., B.D. SHIVER, AND J.W. RHENEY. 1996. *Yield prediction for mechanically site-prepared slash pine plantations in the Southeastern Coastal Plain.* University of Georgia, Warnell School of Forestry and Natural Resources, Plantation Management Research Cooperative Tech. Rep. 1996-3, Athens, GA.

POWERS, R.F., D.A. SCOTT, F.G. SANCHEZ, R.A. VOLDSETH, D. PAGE-DUMROESE, J.D. ELLIOF, AND D.M. STONE. 2005. The North American long-term soil productivity experiment: Findings from the first decade of research. *For. Ecol. Manage.* 220:31–50.

PRITCHETT, W.L., AND R.F. FISHER. 1987. *Properties and management of forest soils*, 2nd ed. John Wiley, New York. 2 p.

REMPEL, R.S., D.W. ANDISON, AND S.J. HANNON. 2004. Guiding principles for developing an indicator and monitoring framework. *For. Chron.* 80:82–90.

ROBERTSON, D.R. 1992. *Pine straw production cost-benefit analysis with species comparisons.* Louisiana State University Agricultural Center, Louisiana Cooperative Extension Service Report, Baton Rouge, LA. 12 p.

SANCHEZ, F.G., D.A. SCOTT, AND K.H. LUDOVICI. 2006. Negligible effects of severe organic matter removal and soil compaction on loblolly pine growth over 10 years. *For. Ecol. Manage.* 227:145–154.

SAYER, E.J. 2006. Using experimental manipulation to assess the roles of leaf litter in the functioning of forest ecosystems. *Biol. Rev.* 81:1–31.

SMIDT, M.F., B. SILVEIRA FOLEGATTI, AND M.R. DUBOIS. 2005. Costs and cost trends for forestry practices in the South. *For. Land Mag.* 64:25–31.

SMITH, J.E., L.S. HEATH, K.E. SKOG, AND R.A. BIRDSEY. 2006. *Methods for calculating forest ecosystem and harvested carbon with standard estimates for forest types of the United States.* USDA For. Serv., Gen. Tech. Rep. NERS-343. 216 p.

STAINBACK, G.A., AND J.R.R. ALAVALAPATI. 2004. Restoring longleaf pine through silvopasture practices: An economic analysis. *For. Policy Econ.* 6:371–378.

SUSAETA, A.I., C.A. GONZALEZ-BENECKE, D.R. CARTER, E.J. JOKELA, AND T.A. MARTIN. 2012. Economical sustainability of pinestraw raking

in slash pine stands in the southeastern United States. *Ecol. Econ.* 80:89–100.

TIMBER MART SOUTH. 2010. *Timber Mart-South market news quarterly*, 4th quarter 2010, vol. 15, no. 4-A. University of Georgia, Warnell School of Forestry and Natural Resources, Athens, GA.

VAN LEAR, D.H., AND N.B. GOEBEL. 1976. Leaf fall and forest floor characteristics in loblolly pine plantations in the South Carolina Piedmont. *Soil Sci. Soc. Am. J.* 40:116–119.

VOGEL, J.G., L.J. SAU, T.A. MARTIN, AND E.J. JOKELA. 2011. Long-term effects of weed control and fertilization on the carbon and nitrogen pools of a slash and loblolly pine forest in north-central Florida. *Can. J. For. Res.* 41:552–567.

WOLFE, K.L., M.J. BEST, AND T. PRICE. 2005. *Pine straw market analysis for southwest Georgia*. University of Georgia, College of Agricultural and Environmental Sciences Center for Agribusiness and Economic Development Market Analysis 05-01, Athens, GA.

ZERPA, J.L., H.L. ALLEN, R.G. CAMPBELL, J. PHELAN, AND H. DUZAN. 2010. Influence of variable organic matter retention on nutrient availability in a 10-year-old loblolly pine plantation. *For. Ecol. Manage.* 259:1480–1489.