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 elliottii* 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 elliottii* 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

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) ($ ha⁻¹·yr⁻¹), and removals of C or nitrogen (N; kg ha⁻¹·yr⁻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 used to determine merchantable volume of forest products. In brief, yearly NF (Mg ha⁻¹·yr⁻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 NF inputs corrected for decay losses using a decay rate of 15% year⁻¹ (Gholz et al. 1985b, 1986, 1991, Binkley, 1992).
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 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 Yokel 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\(_t\) was modeled as follows

\[
PV_t = \exp^{-\delta t} \left[ p_d v_{st} (t) + p_{ps} v_{ps} (t) + p_{pw} v_{pw} (t) \right] + \exp^{-h_t} p_{th} v_{th} - \sum_{i=0}^{t-1} \gamma_i (t) \exp^{-\delta t} \tag{1}
\]

where \(v_{st}(t), v_{ps}(t)\), 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 \(t_0\) (years). Let \(p_{st} = p_{ps} + p_{ps}\), and \(p_{th}\) denote the stumpage prices for sawtimber, chip-and-saw, pulpwood, and thinned material in US dollars m\(^{-3}\), respectively, and let \(\Gamma(t)\) and \(\Sigma(t)\) 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

\[
PV_{ps} = \left[ \sum_{i=0}^{t-1} p_{ps} p_{ps} v_{ps} (t) \exp^{-\delta t} - \sum_{i=0}^{t-1} c_{ps} (t) \exp^{-\delta t} \right] \tag{2}
\]

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 \(\Sigma_{i=0}^{t-1} p_{ps} v_{ps}(t)\) represents the cumulative economic returns due to pinestraw raking between initial time \(t_i\) and time \(t\). The term \(\Sigma_{i=0}^{t-1} c_{ps}(t)\) represents the cumulative costs associated with pinestraw raking production ($ ha\(^{-1}\)) between initial time \(t_i\) 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

\[
LEV(t) = \frac{PV_t + PV_{ps}}{1 - \exp^{-\delta t}} \tag{3}
\]

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, \(p_{st}\) 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

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

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Period of raking (yr)</th>
<th>Raking frequency</th>
<th>Weed management</th>
<th>Fertilization</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thinned</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>R1t</td>
<td>8 until rotation age</td>
<td>Every other year</td>
<td></td>
<td></td>
</tr>
<tr>
<td>R2t</td>
<td>8 until rotation age</td>
<td>Annually</td>
<td></td>
<td></td>
</tr>
<tr>
<td>R3t</td>
<td>8 until yr 15</td>
<td>Every other year</td>
<td></td>
<td></td>
</tr>
<tr>
<td>R4t</td>
<td>8 until yr 15</td>
<td>Annually</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Unthinned</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>R1u</td>
<td>8 until rotation age</td>
<td>Every other year</td>
<td></td>
<td></td>
</tr>
<tr>
<td>R2u</td>
<td>8 until rotation age</td>
<td>Annually</td>
<td></td>
<td></td>
</tr>
<tr>
<td>R3u</td>
<td>8 until yr 15</td>
<td>Every other year</td>
<td></td>
<td></td>
</tr>
<tr>
<td>R4u</td>
<td>8 until yr 15</td>
<td>Annually</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

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 B1, and \(B_2 N = 701\) 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).
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 O1 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), 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 (pinestraw raking forestry [PSF]) versus stands managed under a traditional forestry (TF) scheme for sites with contrasting levels of SI (pinestraw raking [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, and R2, scenarios (Dickens et al. 2007a). Based on Barlow and Dubois (2011), Fox 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\(^{-1}\) 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 pw was set at $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 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\(^{-1}\)).

<table>
<thead>
<tr>
<th>Scenario</th>
<th>LEV ($ ha(^{-1}))</th>
<th>RA (yr)</th>
<th>NR</th>
<th>PV(_{ps}) ($ ha(^{+1}))</th>
<th>C (Mg ha(^{-1}))</th>
<th>N (kg ha(^{-1}))</th>
<th>ENRE-C</th>
<th>ENRE-N</th>
</tr>
</thead>
<tbody>
<tr>
<td>R(_1)u</td>
<td>4,386</td>
<td>26</td>
<td>10</td>
<td>637</td>
<td>6.5</td>
<td>121.7</td>
<td>0.67</td>
<td>36.04</td>
</tr>
<tr>
<td>R(_2)u</td>
<td>6,091</td>
<td>26</td>
<td>19</td>
<td>1,739</td>
<td>12.0</td>
<td>232.5</td>
<td>0.51</td>
<td>26.20</td>
</tr>
<tr>
<td>R(_3)u</td>
<td>3,328</td>
<td>22</td>
<td>4</td>
<td>156</td>
<td>1.3</td>
<td>45.4</td>
<td>2.56</td>
<td>73.30</td>
</tr>
<tr>
<td>R(_4)u</td>
<td>4,283</td>
<td>22</td>
<td>8</td>
<td>715</td>
<td>2.9</td>
<td>92.1</td>
<td>1.48</td>
<td>46.50</td>
</tr>
<tr>
<td>R(_1)t</td>
<td>3,955</td>
<td>24</td>
<td>9</td>
<td>191</td>
<td>5.8</td>
<td>96.6</td>
<td>0.68</td>
<td>40.94</td>
</tr>
<tr>
<td>R(_2)t</td>
<td>5,146</td>
<td>24</td>
<td>17</td>
<td>926</td>
<td>10.5</td>
<td>182.3</td>
<td>0.49</td>
<td>28.23</td>
</tr>
<tr>
<td>R(_3)t</td>
<td>3,547</td>
<td>22</td>
<td>4</td>
<td>156</td>
<td>1.3</td>
<td>45.4</td>
<td>2.73</td>
<td>78.13</td>
</tr>
<tr>
<td>R(_4)t</td>
<td>4,501</td>
<td>22</td>
<td>8</td>
<td>715</td>
<td>2.9</td>
<td>92.1</td>
<td>1.55</td>
<td>48.87</td>
</tr>
</tbody>
</table>

R\(_1\), raking every other year from age 8 years until rotation age; R\(_2\), raking annually from age 8 years until rotation age; R\(_3\), raking every other year 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 rakings.
Table 3. Comparison of LEV, PV<sub>p</sub>, C and N removals, and ENRE-C and ENRE-N for different SI and PD combinations for all raking scenarios with slash pine.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>LEV (Mg ha&lt;sup&gt;-1&lt;/sup&gt;)</th>
<th>PV&lt;sub&gt;p&lt;/sub&gt; (kg ha&lt;sup&gt;-1&lt;/sup&gt;)</th>
<th>N (kg ha&lt;sup&gt;-1&lt;/sup&gt;)</th>
<th>ENRE-C</th>
<th>ENRE-N</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>($ ha&lt;sup&gt;-1&lt;/sup&gt;)</td>
<td>($ ha&lt;sup&gt;-1&lt;/sup&gt;)</td>
<td>($ kg ha&lt;sup&gt;-1&lt;/sup&gt;)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>R1&lt;sub&gt;u&lt;/sub&gt;</td>
<td>501</td>
<td>198</td>
<td>4.1</td>
<td>77.6</td>
<td>0.12</td>
</tr>
<tr>
<td>R2&lt;sub&gt;u&lt;/sub&gt;</td>
<td>1,609</td>
<td>1,001</td>
<td>7.8</td>
<td>163.7</td>
<td>0.21</td>
</tr>
<tr>
<td>R3&lt;sub&gt;u&lt;/sub&gt;</td>
<td>350</td>
<td>259</td>
<td>2.4</td>
<td>57.6</td>
<td>0.40</td>
</tr>
<tr>
<td>R4&lt;sub&gt;u&lt;/sub&gt;</td>
<td>725</td>
<td>295</td>
<td>1.8</td>
<td>57.6</td>
<td>0.40</td>
</tr>
</tbody>
</table>

R1<sub>t</sub> | 265 | -93 | 3.7 | 61.6 | 0.07 | 4.30 | 9,009 | 385 | 2.2 | 63.7 | 4.10 | 141.43 | 3,204 | 26 | 1.1 | 35.6 | 2.91 | 90.00 |
| R2<sub>t</sub> | 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 |
| R3<sub>t</sub> | 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 |

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. For slash stands with SI = 14 m, PD = 1,500 trees ha<sup>-1</sup> and SI = 26 m, PD = 750 trees ha<sup>-1</sup>, and SI = 20 m, PD = 2,250 trees ha<sup>-1</sup>, respectively. For slash stands with SI = 14 m, PD = 1,500 trees ha<sup>-1</sup>, and SI = 26 m, PD = 750 trees ha<sup>-1</sup>, we expect lower removals for both C and N. Opposite sites, such as increase removals, were also associated with pinestraw raking on higher. The effect of SI and PD on profitability and C and N removals were the same for both C and N. Opposite sites, such as increase removals, were also associated with pinestraw raking on higher. The optimal rotation age for the every-other-year scenarios was always longer than the optimal rotation age for the every-other-year scenarios. Furthermore, the rotation ages for all raking scenarios were always 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 options, LEV was obtained with the inclusion of pinestraw raking, given uncertainty about the future effects of those nutrient removals. Specifically, we put forward ENRE (the net revenues per tonne of nutrient removal) as a possible approach for the management of pinestraw raking. Economic Indicators and C and N Removals

The LEVs, PV<sub>p</sub>, C and N removals, and ENRE-C and ENRE-N for all scenarios are presented in Table 2. For slash stands with SI = 14 m and PD = 1,500 trees ha<sup>-1</sup>, higher LEVs were obtained with the inclusion of pinestraw raking, given uncertainty about the future effects of those nutrient removals. Specifically, we put forward ENRE (the net revenues per tonne of nutrient removal) as a possible approach for the management of pinestraw raking. Economic Indicators and C and N Removals
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 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, the 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...
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 \( \geq \) 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 \( \geq \) 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.
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.

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