



Analysis

Economical sustainability of pine straw raking in slash pine stands in the southeastern United States

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ABSTRACT

Raking pine straw for use as landscape mulch has gained popularity over the last two decades in the southern U.S. as an intermediate income source for forest landowners, despite uncertainties associated with its long term impact on soil fertility. A Reed model was utilized to ascertain the effects of pine straw raking on the profitability of slash pine stands. A model that estimates yearly needlefall was employed to determine the nutrient removals due to pine straw raking. The land expectation value (LEV) for the intensively yearly raked unthinned and thinned stands was \$6091 ha⁻¹ and \$5142 ha⁻¹, respectively. Corresponding removals of carbon (C) and nitrogen (N) were 12 Mg ha⁻¹ and 233 kg ha⁻¹, and 11 Mg ha⁻¹ and 182 kg ha⁻¹ for unthinned and thinned stands, respectively. Stands intensively managed for pine straw raking were more profitable than those extensively managed, although nutrient removals were greater under the intensive management scenario. Extensively managed and raked stands were more efficient in terms of nutrient removal and economic revenues. From a land stewardship perspective, managing for pine straw on higher productivity stands may be more efficient in terms of realizing increased economic returns for similar levels of nutrient removal.

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1. Introduction

The use of freshly fallen pine needles (pine straw) for landscape mulch has become a common economic activity in the southeastern United States (U.S.) due to its low cost, easy implementation and absence of competitors (Morris et al., 1992). Longleaf pine (*Pinus palustris* Mill.) and slash pine (*Pinus elliottii* Engelm. var. *elliottii*) are preferred species for pine straw raking over loblolly pine (*Pinus taeda* L.), since their longer and thicker needles decompose more slowly than other species and they maintain desirable color characteristics (Casanova, 2007). Typically, pine straw contractors lease forest stands for consecutive years to rake, bale and market pine straw and, depending upon the contract terms, the landowner receives payments on a per hectare or per bale basis (Duryea, 1989; Morris et al., 1992). However, landowners are becoming more active in forestland management for sustainable pine straw production as this market continues to grow (Patrick Minogue, School of Forest Resources and Conservation, University of Florida, February 13th, 2011, personal communication). Pine straw has become a profitable enterprise in the southeastern U.S., providing a new source of employment and benefiting rural economies. For example, in Florida the

size value of this industry reached US\$80 million in 2005 (Minogue et al., 2007), and in Georgia it generated around US\$60 million annually to the state's economy (Casanova, 2007).

The main objectives of this paper were to internalize the environmental benefits associated with pine straw raking such as the abatement of catastrophic risks and disadvantages such as carbon and nutrient removals, and analyze the implications on forestland profitability. Previous studies have investigated the economic benefits of pine straw raking on southern pines (Dickens et al., 2007a; Morris et al., 1992; Robertson, 1992; Stainback and Alavalapati, 2004). Pine straw raking might increase the profitability of forest stands from \$24–324 ha⁻¹ year⁻¹ (Haywood et al., 1998; Robertson, 1992). Other conservative estimates suggest annual payments ranging from \$173 to 247 ha⁻¹ year⁻¹ (Minogue et al., 2007). However, these studies have not included the risk of wildfires – a crucial component of economic assessment of southern pines (Haight et al., 1995) – and empirically modeled the removal of carbon and nutrients.

Pine needles are considered the main source of surface fuels for carrying fires¹ in southern pine forests (Marshall et al., 2008) and

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¹ Fire is recognized as a natural component of forest ecosystems (Pausas and Keeley, 2009) and was frequently used in the U.S. by early European settlers for land use change and wildfire protection (Andreu and Hermansen-Baez, 2008). Current fire suppression policies have led to increased fuel loads in the southeastern U.S., increasing wildfire risk and threatening human populations in the wildland urban interface (Gaither et al., 2011).

particularly near homes and structures in the wildland urban interface (Monroe et al., 2003). Reductions in live and dead fuel may decrease the spread and severity of wildfires (Waldrop et al., 2008), depending on the level of moisture of live fuels and the amount and spatial distribution of dead fuels (Marshall et al., 2008). Thus, removal of pinestraw represents a management alternative for maintaining low levels of litter biomass in order to minimize the intensity and occurrence of wildfires (Clark and Saunders, 2009; Dodge, 1972; Haywood, 2009; Haywood et al., 1998; Manzello et al., 2006; McLeod et al., 1979; Pearson et al., 1995; Shang et al., 2004; Stephens and Ruth, 2005). Wildfire risk is typically modeled as a function of the forest stand age (Amacher et al., 2005a). The triangular distribution, a probability function that depends on the frequency of fire, is commonly used when the quantitative information about the relationship between the stand age and fire risk is scarce (Li et al., 1997).

Concerns about the negative impacts on carbon (C) dynamics and nutrient availability and long term forest productivity have been associated with pinestraw raking² or forest floor or litter removal (Lopez Zamora et al., 2001; Morris et al., 1992; Pritchett and Fisher, 1987). Sayer (2006) reviewed studies of litter removal in forests worldwide and concluded that long term litter removal severely decreased soil and foliar nutrient concentrations, causing a decline in tree growth. Experiences from Central Europe, where litter removal was a common activity during the 19th century until the 1950s, showed a reduction of 15% in foliar nitrogen concentrations (Nemec, 1929; Sayer, 2006). Furthermore, 50% reductions in growth rates of stands planted in previously raked sites compared to stands planted in unraked soils were found (Mitscherlich, 1955; Sayer, 2006; Wiedemann, 1935). Jandl et al. (2002) concluded that tree growth declined 50% between the 19th century and the first half of the 20th century due to litter raking in the European Alps.

Mixed impacts of litter removal have been found in U.S. studies. Jemison (1943) and Lunt (1951) reported a small detrimental effect on the rate of growth in diameter and stem volume in shortleaf pine (*Pinus echinata* Mill.) and red pine (*Pinus resinosa* Ait.), respectively. McLeod et al. (1979) also observed reductions in growth during the first year after litter raking in longleaf pine. Ross et al. (1995) and Haywood et al. (1998) found no significant effects on tree growth in longleaf pine after two, 3-year intervals and a 5-year period pinestraw raking interval, respectively, and Lopez Zamora et al. (2001) documented no impact on the growth of slash pine after 4 years of pinestraw raking. Similarly, Powers et al. (2005), Sanchez et al. (2006), and Zerpa et al. (2010) found no negative effect on loblolly pine growth 10 years after the complete removal of the forest floor at the time of planting. In spite of these inconclusive results, it is essential to account for the removal of carbon and nutrients due to pinestraw raking to ensure sustainable forest productivity.

With the exception of the approach proposed by Gonzalez-Benecke et al. (in press), limited empirical models have been developed to quantify removals of C and nutrients due to pinestraw raking activities. We coupled this biophysical model with a modified version of the Reed economic approach (1984) to assess the long term economic and C and nutrient removal effects of pinestraw management in southern pine forests. Specifically, we explored and discussed the following: i) the effect of reduction of the probability of wildfires on the profitability of the forest stand and impact on C and nutrient balance due to extensive and intensive pinestraw raking, ii) the impact on the profitability of the forest stand and C and nutrient balance due to pinestraw raking through changes in site index and tree density, iii) the efficiency of different scenarios for pinestraw raking in terms of the expected economic rents and C and nutrient removals, and iv) the sustainable silvicultural practices used for pinestraw raking in southern pines.

² Other concerns associated with pinestraw raking are related to the negative impacts on physical properties of the soil (Patterson et al., 2010) and changes in biodiversity, particularly species richness and composition (Kelly and Wentworth, 2009; Kelly et al., 2000, 2002; Ober and DeGroote, 2011).

2. Material and Methods

2.1. Risk of Fire and Economic Model

Following Reed (1984), we assumed that the fire occurrence probability followed a non homogenous random Poisson process, with a distribution parameter λ dependant on stand age, i.e. $\lambda = \lambda(X)$. The λ parameter represented the probability of occurrence of a fire in any given year. Traditionally, forest age dependent models of probability of fire have approached the ignition of a forest stand as an increasing function of the stand age³ (Amacher et al., 2005a, 2005c; Li and Apps, 1996; Li et al., 1997; Reed, 1984). Consider for example, a forest that had accumulated flammable materials over time such as dead wood, branches and debris. Thus, we assumed a rising fire arrival rate as forest stand ages, i.e. $\lambda'(X) > 0$.

Let X denote a random variable that represents the time between successive fire occurrences that damage the forest, i.e., the age of the stand at the time when fire occurs. X follows an exponential distribution with cumulative density function $(1 - e^{-m(x)})$, where $m(X) = \int_0^X \lambda(q) dq$ and is increasing in X , thus $\frac{dm}{dX} = \lambda(X)$. The probability that the stand is affected by a fire before reaching the optimal rotation age is $Prob(X < T) = 1 - e^{-m(T)}$. At the optimal rotation age ($X = T$), the forest has not been affected by a fire and the probability that the optimal rotation age will be reached and the forest harvested without a fire is $Prob(X = T) = 1 - Prob(X < T) = e^{-m(T)}$. The probability density function of X before reaching the optimal rotation age ($0 \leq X < T$) is given by $\lambda(X)e^{-m(X)}$.

From a forest landowner's perspective the net revenues from a rotation (Y) will depend on two states of the world: the stand reaches the optimal rotation age without a fire, and a destructive fire occurs before the optimal rotation age. In the first state of the world (Y_1), the landowner will harvest the forest stand at the optimal rotation age T without being affected by a fire and replant a new forest stand. If a fire occurs at time X before the forest reaches the optimal rotation age T (second state of the world Y_2), the landowner will salvage a random portion k_X of the timber with mean \bar{k}_X , and replant a new forest stand. Costs associated with the establishment and development of a forest stand are independent of the salvageable portion. Salvage logging⁴ is primarily driven by potential economic returns and reductions in fuel loads that decrease the probability of fire (Brown et al., 2003; Thompson and Spies, 2010). However, salvage logging might increase the fire hazard due to an increase in fine fuel materials (McIver and Ottmar, 2007) and also have negative impacts on stand structural complexity, ecosystem process and functions, population species and community composition (Lindenmayer and Noss, 2006).

Let's assume a forest stand produces traditional forest products (e.g. sawtimber, chip and saw, pulpwood) and pinestraw bales. Let P and P_{sr} denote the forest product price, and price of the pinestraw bale, respectively. We also assume a fixed thinning before the optimal rotation age T , with a net price of thinned wood P_{th} and volume of thinned wood V_t . Let $V(T)$ and $V_b(n)$ denote the merchantable volume of the forest at rotation age T , and the number of pinestraw bales harvested at age n , respectively. Also let $\sum_{t_0}^T C(T)$ and $\sum_{t_b}^T C_b(T)$ represent the cumulative silvicultural costs associated with the

³ Age independent models of probability of fire (homogenous Poisson process) have been assumed by Amacher et al. (2005b, 2006), Englin et al. (2000), Reed (1984, 1987), and Susaeta et al. (2009) where an average fire occurrence rate ranges between 1% and 4%. Similar hazard rates in forests – between 0.5% and 2% – were also postulated by Runkle (1985).

⁴ Modeling of timber salvage has endogenously relied on characteristics of the forest. Amacher et al. (2005a, 2005b, 2005c) approached it as a function of planting density and level of fuel treatment, ranging the salvageable portion between 60% and 90%. Pasalodos-Tato et al. (2009) determined it as an increasing function of the diameter at breast height of the tree. Empirically, Outcalt and Wade (2004) claimed dissimilar tree mortality rates of southern pines after wildfires in Florida: 3.5% and 43% of mortality rate in natural forest stands and plantations, respectively.

establishment and development of a forest stand, and intermediate silvicultural costs associated with the production of pinestraw, between time periods t_0 and T , and t_b and T , respectively. The net current (undiscounted) economic rents, Y_1 , for the first rotation in the first state of the world, when the forest stand reaches the optimal rotation age ($X = T$) without being affected by a fire, are:

$$Y_1 = PV(T) + (P_{th}V_t)exp^{\delta(T-t)} + \sum_{j=t_0}^T P_{sr}V_b(n) exp^{\delta(T-j)} - \sum_{t_0}^T C(T)exp^{\delta(T-t_0)} - \sum_{t_b}^T C_b(T)exp^{\delta(T-t_b)}$$

if $X = T; n = j, \dots, T; t, j > 0; t_0 \geq 0; t_b > 0$

$$(1)$$

Eq. (1) says that a landowner will realize future economic rents due to tree harvesting at the optimal rotation age ($PV(T)$), compounded thinning benefits ($(P_{th}V_t)exp^{\delta(T-t)}$) and cumulative returns due to pinestraw raking between time periods j and T ($\sum_j^T P_{sr}V_b(n) exp^{\delta(T-j)}$). In addition, a landowner has incurred the compounded cumulative costs associated to establish and develop a forest stand ($\sum_{t_0}^T C(T) exp^{\delta(T-t_0)}$), and production of pinestraw ($\sum_{t_b}^T C_b(T) exp^{\delta(T-t_b)}$).⁵ The net current economic rents Y_2 for the first rotation in the second state of the world, the fire shortened rotation, are:

$$Y_2 = \tilde{k}_X PV(X) + P_{th}V_x exp^{\delta(X-x)} - \sum_{x_0}^X C(X) exp^{\delta(X-x_0)} - \sum_{x_b}^X C_b(X) exp^{\delta(X-x_b)}$$

if $X < T; x, j > 0; x_0 \geq 0; x_b > 0$

$$(2)$$

Eq. (2) says that following a fire at time period X , a landowner realizes a proportion \tilde{k}_X of future timber benefits accruing due to tree harvesting ($PV(X)$). If a fire occurs after time x , he/she also realizes the compounded thinning benefits ($P_{th}V_x exp^{\delta(X-x)}$). Revenues from the fixed thinning at time x are ruled out if the fire occurs when $X < x$. Under the assumption that trees exposed to wildfire experience 100% consumption of foliage (Hurteau and North, 2009; Reinhardt and Crookston, 2003), the cumulative returns due to pinestraw raking between time periods j and X are set to zero. A key assumption of our model also is that there is a probability of fire that can affect the forests stand each year – given that X is the random time between successive fire occurrences, or also known as the age of the stand. Then, Eq. (2) is basically the representation of net economic revenues with a partial destruction of the stand, i.e., when timber salvage is allowed, due to random fire occurrence. The underlying assumption is that a fire event may happen every year. A landowner is annually economically compensated due to timber salvage but he/she is not able to salvage any proportion of needlefall production, thus, the returns due to pinestraw raking are not considered in Eq. (2).⁶ On the cost front, at the time of fire occurrence the landowner has already incurred silvicultural costs for development of the stand ($\sum_{x_0}^X C(X) exp^{\delta(X-x_0)}$) and pinestraw raking ($\sum_{x_b}^X C_b(X) exp^{\delta(X-x_b)}$). The latter is ruled out if the fire occurs when $X < x_b$.

Following Reed (1984), the land expectation value (LEV), assuming an infinite time horizon can be modeled as:

$$LEV(T) = \frac{E[\exp^{-\delta X} Y]}{1 - E[\exp^{-\delta X}]} \quad (3)$$

⁵ We present the generalized case in which the benefits and costs due to pinestraw raking are obtained, respectively between time periods j and T , and t_b and T . In the following section, we show that the timing of benefits and costs may be different (before optimal rotation age T) depending on the pinestraw raking regime.

⁶ In other words, with a yearly partial destruction of the stand, there is no possibility of harvesting pinestraw prior to a fire, i.e., a landowner cannot anticipate a fire event. On the contrary, without fire risk, a landowner can only harvest the forest stand once and obtain benefits due to pinestraw raking even until the rotation age (Eq. (1)).

Where δ is the discount rate. The expectation for the denominator term in Eq. (3) can be expressed as (Amacher et al., 2009):

$$E[\exp^{-\delta X}] = \int_0^T \exp^{-[\delta X + m(x)]} dx = \frac{\delta \exp^{-[m(T) + \delta T]}}{\lambda(T) + \delta} \quad (4)$$

In addition,

$$E[\exp^{-\delta X} Y] = \exp^{-\delta T} Y_1 \exp^{-m(T)} + \int_0^T \exp^{-\delta X} Y_2 \lambda(X) \exp^{-m(x)} dx \quad (5)$$

The expected discounted value of the net economic returns for the first rotation of the stand⁷ under the risk of fire (the numerator term in Eq. (3)) is the sum of the value of the forest affected by a fire with a salvageable portion of the timber harvested before the optimal rotation age, and the value of the forest harvested at the optimal rotation age. It is important to mention that without the risk of fire, the right hand side of Eq. (5) becomes the traditional net present value for the first rotation represented by the first state of world ($\exp^{-\delta T} Y_1$). Although we ruled out the possibility of salvaging any proportion of needlefall production for the partial destruction of the stand, this model does consider the cumulative returns due to pinestraw raking under the risk of fire. It is accounted for in the first term on the right-hand side of Eq. (5). At first glance, this can be counterintuitive since Y_1 represents the total benefits without the risk of catastrophic events. However, the risk of fire is included in the discounted rate that brings the future returns due to pinestraw raking (along with timber benefits) back to the present, having a negative impact on profitability. Using Eqs. (3) and (4) the LEV can be written as:

$$LEV(T) = \frac{\lambda(T) + \delta}{\delta [1 - \exp^{-m(T) - \delta T} + \lambda(T)]} [\exp^{-\delta T} Y_1 \exp^{-m(T)} + \int_0^T \exp^{-\delta X} Y_2 \lambda(X) \exp^{-m(x)} dX] \quad (6)$$

Eq. (6) represents the traditional Faustmann formula without the risk of fire. From Eqs. (1), (2) and (5), the net present value of pinestraw raking (NPVr) is given by the following expression:

$$NPVr = \exp^{-\delta T} \left[\left(\sum_j^T P_{sr}V_b(n) \exp^{\delta(T-j)} - \sum_{t_b}^T C_b(T) \exp^{\delta(T-t_b)} \right) e^{-m(T)} + \int_0^T \exp^{-\delta X} \lambda(X) \left[-\sum_{x_b}^X C_b(X) \exp^{\delta(X-x_b)} \right] \exp^{-m(X)} dX \right] \quad (7)$$

On the right-hand side of Eq. (7), the terms $\sum_j^T P_{sr}V_b(n) \exp^{\delta(T-j)}$ and $\sum_{t_b}^T C_b(T) \exp^{\delta(T-t_b)}$ are part of Y_1 and $\sum_{x_b}^X C_b(X) \exp^{\delta(X-x_b)}$ is part of Y_2 in Eqs. (5) and (6). We take the first derivative of Eq. (6) with respect to time T and set it equals to zero to find the expected optimal rotation age T^* . We solve it by hand to obtain the following expression:

$$PV(T)' + \sum_j^T P_{sr}V_b(n)' \exp^{\delta(T-j)} - \sum_{t_0}^T C(T)' \exp^{\delta(T-t_0)} - \sum_{t_b}^T C_b(T)' \exp^{\delta(T-t_b)} = \lambda(T) \{ (1-k) \left[PV(T) + P_{th}V_t \exp^{\delta(T-t)} + \sum_j^T P_{sr}V_b(n) \exp^{\delta(T-j)} \right] \} + \delta PV(T) + \delta LEV(T)$$

Eq. (8) represents the rule of harvesting of a stand that produces traditional forest products along with pinestraw bales. The left-hand side is the marginal revenue value of waiting one extra year while the right-hand side is the marginal cost of waiting one more year (cost of holding the current forest stand plus the cost of holding the

⁷ Intuitively, this model also determines the profitability of forestlands under the risk of fire ruling out the production of pinestraw and/or thinnings by setting $P_{th}V_t$, $\sum_j^T P_{sr}V_b(n)$, and $\sum_{t_b}^T C_b(T) = 0$.

land). If the marginal revenue of waiting is higher than the marginal cost of waiting, the landowner should wait one more year to harvest. In the contrary case the forest stand should be harvested.

3. Model Application to Slash Pine Stands

Slash pine is a fast growing species native to the southern U.S. that has been planted on more than 4.2 million ha, covering a wide range from eastern Texas to southern North Carolina to south-central Florida (Barnett and Sheffield, 2005). Around 79% of the planted slash pine occurs in Florida and Georgia (Barnett and Sheffield, 2005). We used whole-stand growth and yield models for slash pine as reported by Pienaar et al. (1996) and Yin et al. (1998), and modified to allow for multiple fertilizer additions (Bailey et al., 1999) and thinning (Bailey et al., 1980; Pienaar, 1995) treatments. Harvested roundwood (from thinnings or final harvests) was assigned to three main product classes depending on stem DBH and merchantable diameter; sawtimber (st), chip-and-saw (cns) and pulpwood (pw) using the model proposed by Pienaar et al. (1996) and Yin et al. (1998). To determine pinestraw production, we employed the model developed by Gonzalez-Benecke et al. (in press), in which yearly needlefall (NF) was estimated as a function of site index (SI, the height reached by the stand's dominant and co-dominant trees at a reference age of 25 years) and stand density index (SDI, the number of trees of 25.4 cm diameter that the stand can support in one hectare for a given basal area, Reineke, 1933). Previous year SDI was correlated with current-year needlefall using a 3-parameter sigmoidal function (Table 1, see Gonzalez-Benecke et al., in press for further details). Yield per hectare (ha) of pinestraw was converted to bales per ha assuming 7.7 kilograms (kg) of pinestraw per bale and a raking efficiency conversion factor of 75% (David Dickens, Warnell School of Forestry and Natural Resources, University of Georgia, February 27th 2011, personal communication).

Using NF C and nutrient concentrations and the model it is possible to estimate C and nutrient removals from pinestraw raking. Net C removal due to pinestraw raking was determined after deducting, at rotation age, the biomass of needles in the forest floor with and without raking. Needle mass in the forest floor (Mg ha^{-1}) was determined as the sum of yearly needlefall inputs corrected for decay loss using a decay rate of $15\% \text{ year}^{-1}$ (Binkley, 2002; Gholz et al., 1985a, 1986, 1991; Gonzalez-Benecke et al., in press). 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 concentrations of nitrogen (N), phosphorus (P), potassium (K), calcium (Ca), and magnesium (Mg) in NF were obtained from published values reported in the peer-reviewed literature, averaging 4.14, 0.26, 0.62, 3.59 and 0.86 g kg^{-1} , respectively (Burger, 1979; Dalla-Tea and Jokela, 1991; Gholz et al., 1985b; Manis, 1977).

Five unthinned and thinned scenarios for pinestraw raking were defined. The age of thinning was set at year 15 when applicable. Table 2 shows the different scenarios with their respective descriptions and silvicultural treatments. Chemical weed control cost of $\$136 \text{ ha}^{-1}$ was assumed for raking activities (Camron Owens, Rayonier Inc, March 2nd 2011, personal communication). For the R1_t and R2_t scenarios, a cleanup cost of $\$173 \text{ ha}^{-1}$ at year 17 was assumed prior to the resumption of raking (Dickens et al., 2007a). A fertilization cost of $\$222 \text{ ha}^{-1}$ was assumed⁸ (Fox et al., 2007).

Common silvicultural management costs for all scenarios were based on Fox et al. (2007), Peter et al. (2007), and Smidt et al. (2005). Costs of $\$493 \text{ ha}^{-1}$ and $\$193 \text{ ha}^{-1}$ were assumed for site preparation (shear, rake, pile and bed) and aerial weed control prior to establishment, respectively. Planting and seedling costs were assumed to be $\$0.085 \text{ plant}^{-1}$ and $\$0.05 \text{ seedling}^{-1}$. Banded weed control and

Table 1

Summary of parameter estimates^a for the yearly needlefall model for slash pine in the southeastern United States.

Parameter	Model
$\ln NF$	$= 0.80235 + 0.96529 \ln \left(\frac{\beta_0}{1+e^{-\left(\frac{SDI-\beta_2}{\beta_1} \right)}} \right)$
β_0	$= 1.37070021 + 0.147580126 SI$
β_1	$= 23.4519 + 2.1389 SI$
β_2	$= \frac{327.2346}{1+(SI/18.5717)^{-4.929}}$

^a NF is current year needlefall biomass ($\text{Mg ha}^{-1} \text{ yr}^{-1}$); SDI is previous year Reineke's stand density index in metric units; β_0 , β_1 and β_2 are sigmoidal fit parameters; SI is stand site index (m).

fertilization costs were assumed to be $\$93 \text{ ha}^{-1}$ at year 1 and $\$222 \text{ ha}^{-1}$, respectively, for all scenarios. Annual management costs were set at $\$20 \text{ ha}^{-1}$ (Siry, 2002). A marking cost of $\$35 \text{ ha}^{-1}$ was assumed for the thinned scenarios.

Average southeastern stumpage prices for st, cns, and pw were $\$31.2 \text{ m}^{-3}$, $\$19.1 \text{ m}^{-3}$, and $\$10.3 \text{ m}^{-3}$, respectively (Timber Mart South, 2010). Price of ps was set to $\$0.5 \text{ bale}^{-1}$. After thinning, the site may not have the same pinestraw yield because of less trees and increased understory competition that reduces the area to be raked (David Dickens, Warnell School of Forestry and Natural Resources, University of Georgia, February 27th 2011, personal communication). Thus, we assumed a 50% pine straw yield reduction after year 15 for the thinned scenarios. A discount rate of 4% was used in all economic analyses.

We considered a forest stand that faced a rising fire risk and any salvageable timber after a fire could be harvested, and replanted to start a new rotation. Following Amacher et al. (2005a, 2005c), and due to the lack of quantitative information about the relationship between stand age and probability of fire (Li et al., 1997), we linearly modeled the fire occurrence rate assuming that $\lambda(X)$ followed a triangular distribution.⁹ Thus:

$$\lambda(X) = \frac{2t_0(X-t_a)}{(t_b-t_a)(t_c-t_a)} \quad (9)$$

Where t_a and t_b are the lower and upper limit of time T , t_c represents the mode value and t_0 is a scale parameter that represents a shift in the magnitude of $\lambda(X)$. We assumed that fire frequency occurred every 50 years, thus $t_a=0$ and $t_b=t_c=50$ and $t_0=1$ and $t_o=0$ (no fire risk). Fire frequency in the U.S. South has typically ranged between 0 and 35 years (Schmidt et al., 2002). Although a fire frequency of 50 years may be considered a conservative estimate, lower fire frequencies – 50 to 100 years – are currently found for southern pines (Flannigan et al., 2000). We assumed that 70% of the stand could be salvaged after a fire, an estimate in agreement with those reported by Amacher et al. (2005a, 2005b, 2005c), Outcalt and Wade (2004), and Stainback and Alavalapati (2004).

At early stages of the stand, even when commercial pinestraw bale production starts, the annual probability of fire may be close to zero due to less amount of flammable material. However, even with a low probability of fire, the amount of pinestraw available after a fire and prior to subsequent fires may not be sufficient to meet the minimum number of bales per hectare to become a profitable enterprise. It is considered the quantity of 370 bales ha^{-1} as a break-even point for contractors to begin raking in slash pine stands (David Dickens, Warnell School of Forestry and Natural Resources, University of Georgia, February 27th 2011). Even if the fire had not consumed all foliage, some features of

⁸ The costs associated with these intermediate treatments for raking purposes are represented by $\sum_{t_0}^T C_b(T)$ described in the previous section. All other costs are represented by $\sum_{t_0}^T C(T)$.

⁹ Li et al. (1997) modeled the hyperbolic, sigmoid and linear increase of probability of fire with stand age and found similar results for all distributions with actual forest regimes in Ontario, Canada.

Table 2

Raking scenarios^a and silvicultural management^b for slash pine in the southeastern United States (native SI = 20 m and TD = 1500 trees ha⁻¹).

Scenarios _u = unthinned _t = thinned	Period of raking (year)	Description	Weed control (year)	Fertilization ^c (year)
NR _u	No raking	Baseline	n.a	n.a
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 year 15	Annually	7, 11, 15	11
R4 _u	8 until year 15	Every other year	7, 11, 15	11
R5 _u	8 until year 15	Raking on years 8, 9 and 10; no raking on years 11 and 12; resume annual raking on years 13, 14 and 15	7, 11, 15	11
NR _t	No raking	Baseline	n.a	n.a
R1 _t	8 until rotation age	Every other year until thinning; resume raking at year 18 until rotation age	7, 11, 15, 19	11, 19
R2 _t	8 until rotation age	Annually until thinning; resume raking at year 18 until rotation age	7, 11, 15, 19	11, 19
R3 _t	8 until year 15	Annually	7, 11, 15	11
R4 _t	8 until year 15	Every other year	7, 11, 15	11
R5 _t	8 until year 15	Raking on years 8, 9 and 10; no raking on years 11 and 12; resume annual raking on years 13, 14 and 15	7, 11, 15	11

^a Hereafter, thinned/unthinned scenarios R1 and R2 will be denoted as intensive raking scenarios; thinned/unthinned scenarios R3, R4, and R5 will be referred as extensive raking scenarios.

^b 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.

^c 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, R4 and R5.

the needles would be affected such as freshness, color and brightness and length degrading the quality of the pinestraw bale. Thus, pinestraw would not meet the minimum standards for landscape mulching. Finally it is not within the scope of our paper to determine the possibility that a portion of the needlefall may be commercially harvested in light of the different levels of wildfire risk. If that were the case, the implications on economic benefits would not be completely clear: there may be more available pinestraw bales due to the option of needlefall salvage, but some of them with inferior quality (low price per bale). Furthermore, more technical effort associated with higher operational costs may be demanded during pinestraw harvest.

We expected that the baseline and raking scenarios would have different probabilities for fire risk. However, effectiveness of fuel load reductions on wildfire behavior and fire damage is controversial. Shang et al. (2004) found that fuel treatments decreased both fire damage and potential fire risk. Amacher et al. (2005a, 2005b, 2005c) and Fernandes and Botelho (2003) suggested that fuel treatments reduced the severity of a fire without affecting the probability of fire occurrence. We modeled baseline scenarios with $t_0 = 1$ and all raking scenarios with $t_0 = 0$. For simulation purposes we allowed the probability of a fire to occur in a forest stand ($t_0 = 1$). As noted earlier, we also quantified the removal of nutrients due to pinestraw raking. Presence of wildfires will burn fine fuels rapidly and alter nutrient availability in the soil, although base cations generally increase (Thiffault et al., 2008). Lavoie et al. (2010) found that total C and N pools and base cations were reduced in the forest floor although base cations increased in the mineral soil after one year. However, it is not within the scope of this paper to quantify the nutrient balance after a fire.

The main sources of variation of the integrated growth and yield model are site index (SI) and number of trees per hectare (TD). Thus, a sensitivity analysis was conducted to determine the effects of these two factors on the profitability of forestlands and C and nutrient removals for the extensively and intensively managed pinestraw raking scenarios.

Using the information regarding forest stand growth function, prices, silvicultural costs, and probability of fire risk described above, we used the Eq. (6) to calculate the LEV for each of the five unthinned and thinned scenarios for pinestraw raking. For example, for the R3_t scenario, we simulated annually, with and without fire risk, expected present perpetual economic returns as a result of the rents due to tree harvesting, thinning at year 15 and cumulative pinestraw raking between years 8 and 15. Likewise, we calculated the expected present value of the cumulative

silvicultural costs associated with the development of the forest stand (site preparation and weed control at year 0, planting and seedling costs at year 1, fertilization at years 5 and 15, and annual management cost) and pinestraw raking (weed control at years 7, 11 and 15, and fertilization at year 11). The LEV was computed from subtracting the present total costs from the total economic returns. The age associated with highest LEV was the optimal rotation age. Similarly, we calculated the LEV for the other scenarios but considering that the timing of the economic benefits or costs due to pinestraw raking may differ depending on the pinestraw raking regime (Table 2).

4. Results and Discussion

4.1. Profitability of Forestlands and Carbon and Nutrient Removals

4.1.1. Comparison between Intensively and Extensively Managed Raking Scenarios

The inclusion of pinestraw raking into traditional forest management regimes resulted in higher LEVs¹⁰ (Fig. 1c). The expected economic returns and nutrient removals depended on the risk of fire. The most profitable scenarios in terms of LEV were those in which the forest stands were most intensively managed for pinestraw raking without the effect of fire ($t_0 = 0$, R2_u and R2_t). The LEVs for these scenarios were \$6091 ha⁻¹ and \$5146 ha⁻¹, respectively. The NPVrs for these scenarios were \$1739 ha⁻¹ and \$926 ha⁻¹. These scenarios, coupled with extended rotation ages – 24 and 26 years, respectively – had the highest nutrient removals. For example, C removals, after 19 and 17 rakings, were 12 and 11 Mg ha⁻¹ for R2_u and R2_t in the absence of risk of fire (Fig. 1a, $t_0 = 0$), respectively. N removals were 233 and 182 kg ha⁻¹ for R2_u and R2_t (Fig. 1b, $t_0 = 0$). On average, LEVs and NPVrs for the intensively managed raking scenarios were 25% and 102% higher than those for extensively managed scenarios. Similarly, removals of C and N were 323% and 9% higher for the intensive compared to the extensive raking scenarios.

In relative terms, higher C and N removals were found for the intensively managed raking scenarios under no risk of fire (Table 3). On average, removal rates of C and N were 53% and 47% for the intensive raking scenarios, and 14% and 30% for the extensive raking scenarios, respectively.

¹⁰ Full information with LEVs, NPVrs, rotation age, number of rakings and all nutrient removals can be found in Table A.1., Appendix A.

Table 3

Total C and N in needles of forest floor with and without raking in slash pines in the southeastern United States.

Scenario	Total C without raking (Mg ha ⁻¹)	Total C after raking (Mg ha ⁻¹)	Total N without raking (kg ha ⁻¹)	Total N after raking (kg ha ⁻¹)
R1 _u	17.4	10.8	338.2	216.4
R2 _u	17.4	5.3	338.2	105.7
R3 _u	16.0	13.0	228.6	136.5
R4 _u	16.0	14.6	228.6	183.2
R5 _u	16.0	13.7	228.6	160.1
R1 _t	17.3	10.8	327.5	230.9
R2 _t	17.0	5.3	327.5	145.2
R3 _t	15.9	13.0	228.6	136.5
R4 _t	15.9	14.5	228.6	183.2
R5 _t	15.9	13.7	228.6	160.1

4.1.2. Comparison between Unthinned/Thinned Intensively and Extensively Managed Raking Scenarios

As expected, the LEVs and the NPVrs for each scenario were increased as the probability of fire decreased. On average the LEVs and NPVrs increased by 71% and 22%, respectively, for the scenarios without thinning when $t_0=0$ (Fig. 1c and d). This positive impact on the land values and net returns from pine straw raking played a lesser role for thinned stands, accounting for average increases of 68% and 17%, respectively. Decreasing the risk of fire and lengthening the rotation age thus would benefit forest landowners since they might realize higher economic rents from intensive pine straw raking. On average, 72% higher LEVs were found for unthinned and thinned intensive raking scenarios, respectively, without the risk of fire. The corresponding NPVrs increased by 59% and 37%. C removals for the unthinned and thinned intensive raking scenarios increased by 4% and 7%, respectively, as the probability of fire decreased (Fig. 1a). N removals increased by 23% and 15% (Fig. 1b). Thinned intensive raking scenarios had 13% and 53% lower LEVs and NPVrs, and 2% and 21% lower C and N removals, respectively, compared to those for the unthinned intensive raking scenarios. This was expected due to a combination of less bale production and raking intensity after thinning, and shorter rotation ages.

Without risk of fire, forest landowners might also be encouraged to undertake thinned, extensively managed pine straw raking scenarios. This is reflected by higher LEVs and NPVrs (Fig. 1c and d), and lower C and N removals (Fig. 1a and b) for scenarios R3_t and R5_t compared to R1_t. Furthermore, reducing the risk of fire was also found to favor higher land values for thinned extensively managed scenarios, with similar levels of C and nutrient removals – 6% higher LEVs on average – compared to those for extensive raking scenarios without thinning.¹¹ This was also expected due to the increased proportion of sawtimber over pulpwood revenues from thinning.

4.2. Sensitivity Analysis

In the sensitivity analyses, SI varied from 14 to 20 m, and TD ranged from 750 and 2250 trees ha⁻¹; economic indicators were compared to the original combination of SI and TD. Fig. 2 shows the LEVs, NPVr for the different SI/TD combinations.

¹¹ The NPVrs and nutrient removals remained constant for each extensively managed scenario regardless of thinning because pine straw raking was imposed only between years 8 and 15. Differences in net C removal were found for these scenarios as it depended on the rotation age.

4.2.1. Effects of Changes in SI on Profitability of Forestlands and C and N Removals

Consistent with expectations, 146% and 137% higher LEVs, and 75% and 94% higher NPVrs were obtained, respectively, for unthinned and thinned scenarios without the risk of fire, when SI = 26 m (Fig. 2a and b). Decreased economic indicators – 90% and 89% lower LEVs and 75% and 94% lower NPVrs – were found when SI = 14 m (Fig. 2a and b). Increased SI implied an increase in stand LAI (Albaugh et al., 1998; Jokela and Martin, 2000) and, therefore, needlefall and stand productivity (Gonzalez-Benecke et al., in press; Martin and Jokela, 2004). Concomitant increases in removals of C and nutrients were also associated with pine straw raking on higher quality sites. On average, the removals of C and N increased by 50% and 34%, respectively, for SI = 26 m compared to those for SI = 20 m,¹² without the risk of fire. On poorer sites, the losses were less – 38% and 36%, respectively, for C and N.

4.2.2. Effects of Changes in TD on Profitability of Forestlands and C and N Removals

Modifying TD had a minor impact on land values when the risk of fire decreased. Lower land values for unthinned and thinned scenarios were found for TD = 2250 trees ha⁻¹ – 1% and 5%, respectively¹³ (Fig. 2c). Dissimilar effects on land values were found for unthinned and thinned scenarios for TD = 750 trees ha⁻¹ – 2% higher and 11% lower LEVs (Fig. 2c). The reduction in TD implied that the production of pine straw bales from ages 8 to 15 years did not reach a maximum and, therefore, the NPVrs were reduced by 43% and 54% for the unthinned and thinned scenarios, respectively (Fig. 2d). Decreased TD implied a lower decrease in C (10%) and N (19%) removals. Increased TD had dissimilar effects on nutrient removal. For the intensive raking scenarios, the change was negligible for C, while for N it increased/decreased by 6.1% and 3% for the intensive unthinned and thinned raking scenarios, respectively. The nutrient removals increased by 8% and 4% for C and N, respectively, for the extensively managed raking scenarios.

SI had a larger impact than TD on nutrient removals.¹⁴ When SI = 26 m and TD = 750 trees ha⁻¹, the nutrient removals were 200% and 111% greater for C and N than those for SI = 14 m and TD = 750 trees ha⁻¹. When SI = 14 m and TD = 2250 trees ha⁻¹, C and N removals were 13% and 18% greater, respectively, compared to those for SI = 14 and TD = 750 trees ha⁻¹.

4.2.3. Efficiency of Pine Straw Raking: Nutrient Balance vs. Economic Revenues

The extensively managed raking scenarios were more efficient in terms of nutrient removals relative to economic revenues. When all simulations under different SI and TD were pooled for each pine straw raking scenario, the relationship between economic revenues and C and N removals was found. For the same NPVr (Fig. 3) and LEV (Fig. 4), removals of C and N were higher for the intensive scenarios (R1 and R2) compared to those of the extensive raking scenarios (R3, R4 and R5) ($p < 0.001$). With the intensive raking scenarios, for each \$100 NPVr increment, the removals of C increased 1.0 and 1.3 Mg C ha⁻¹, for unthinned and thinned stands, respectively. On the other hand, the extensive raking scenarios removed 0.74 Mg C ha⁻¹ for each \$100 NPVr increment. In the case of N, the average rates of change were 9.7 and 11.2 kg N ha⁻¹ for

¹² A complete table with removal of nutrients for all raking scenarios is available from authors upon request.

¹³ Although overstocked forest stands reached a maximum LAI at younger ages and stimulated higher needlefall production levels, negative impacts on profitability occurred because of higher planting costs and the production of lower market priced pulpwood in the densely spaced stands.

¹⁴ We also quantified the estimates for economic indicators and nutrient removals from the cross effects between SI and TD. For example, SI = 14 m with TD = 750 and 2250 trees ha⁻¹; SI = 26 m with TD = 750 and 2250 trees ha⁻¹. A complete table with LEVs, NPVrs, and removal of nutrients for all raking scenarios is available from authors upon request.

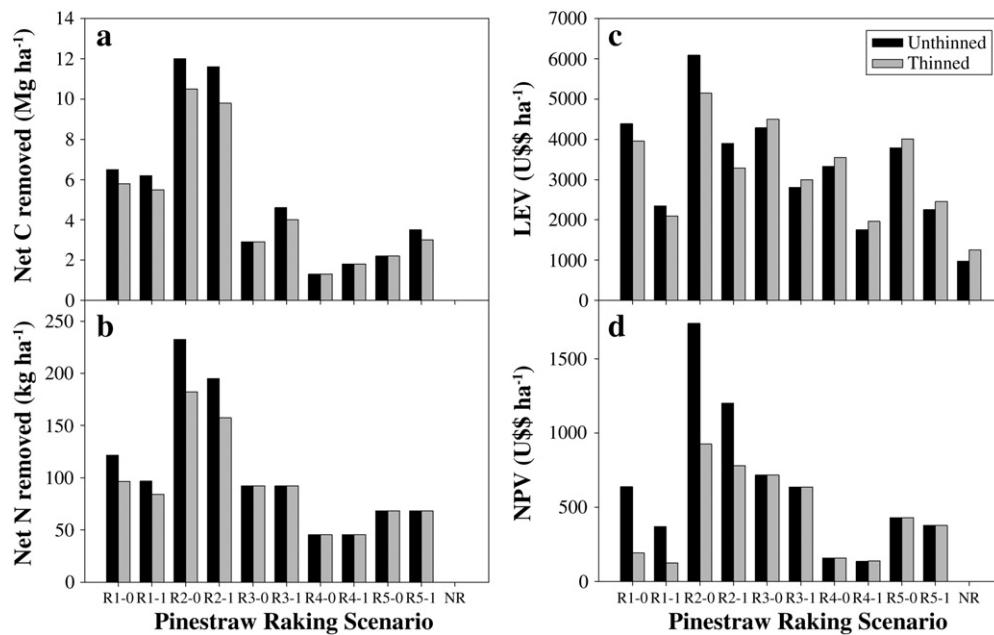


Fig. 1. LEV (c) and NPVr (d) and removals of C (a) and N (b) for unthinned and thinned raking scenarios at different levels of risk of fire.

each \$100 NPVr, for unthinned and thinned stands with the intensive raking scenarios, and 8.2 kg N ha^{-1} for each \$100 NPVr, for the extensive raking scenarios.

Pine straw raking in thinned stands removed more C and N per unit change in NPVr than in unthinned stands ($p < 0.001$). Thus, forest landowners might be inclined to rake less in light of the potential negative impacts of nutrient removal on long term site productivity. For the same revenues from raking, nutrient removals were higher for the thinned, intensive raking scenarios. Forest landowners would then have to rake more intensively and remove more C and N to equate to revenues in the unthinned raking scenarios (Fig. 3).

Slash pine plantations on sites with higher potential productivity were more efficient in C and nutrient removal per unit economic revenue increment. For any given level of C and nutrient removal, the LEVs were larger in stands with higher SI. For an average C removal of 5 Mg ha^{-1} , stands with $SI = 14, 20$ and 26 m averaged a LEV of $\$780 \text{ ha}^{-1}$, $\$3740 \text{ ha}^{-1}$, and $\$8900 \text{ ha}^{-1}$, respectively (Fig. 4a). In the case of N, for an average pine straw removal of 100 kg ha^{-1} , the LEV of stands with $SI = 14, 20$ and 26 m averaged $\$1240 \text{ ha}^{-1}$, $\$4290 \text{ ha}^{-1}$, and $\$9500 \text{ ha}^{-1}$, respectively (Fig. 4b). From a land stewardship perspective, it may be more efficient to manage for pine straw on higher SI stands, as financial returns are higher for similar levels of nutrient removal.

Different TDs would be selected for sites with different inherent site qualities to maximize profits per nutrient removed for the extensive raking scenarios (Fig. 5). On higher quality sites ($SI = 26 \text{ m}$; Fig. 5b), landowners would maximize LEVs if planting density was increased. For a stand growing on a low quality site ($SI = 14 \text{ m}$; Fig. 5a), landowners would be stimulated to plant less trees to realize higher economic revenues due to an increased proportion of sawtimber being produced compared to pulpwood.

4.3. Sustainable Practices for Pine Straw Raking

Important conclusions from these sensitivity analyses were that modifying site quality had a greater impact on land values compared to changes in the tree density when the risk of fire was reduced. Furthermore, planting on more productive sites would be more efficient in terms of sustainability, as land values tend to be higher and C and N removals per unit economic revenues were lower. Thus, forest landowners should focus their efforts on implementing management practices such as fertilization, weed control, and planting genetically

improved seedlings – particularly fusiform rust seedlings – for increasing the overall productivity of the site¹⁵ (Jokela et al., 2010).

The application of fertilizer is a silvicultural option used to counteract the loss of nutrients due to pine straw raking (Dickens et al., 2007a; Dickens et al., 2007b; Dickens et al., 2010; Minogue et al., 2007; Morris et al., 1992). On average, across all forest management scenarios analyzed ($SI = 20 \text{ m}$ and $TD = 1500 \text{ trees ha}^{-1}$; Fig. 1) and for any single pine straw harvest, the nutrient removals in harvested pine straw bales were around 11.4 kg ha^{-1} of N, 0.8 kg ha^{-1} of P, 1.0 kg ha^{-1} of K, 12.2 kg ha^{-1} of Ca and 3.4 kg ha^{-1} of Mg, respectively. As Morris et al. (1992) pointed out, even though nutrient removals in a single pine straw harvest are small, they come to be large in stands repeatedly raked.

For example, for a stand with annual pine straw raking from ages 8 to 15 years (i.e. scenario R3, $SI = 20 \text{ m}$, $TD = 1500$, Fig. 1 and Table A.1), it would be necessary to apply 200 kg ha^{-1} of urea, 38 kg ha^{-1} of triple superphosphate, 13 kg ha^{-1} of muriate of potash, 246 kg ha^{-1} of lime, and 173 kg ha^{-1} of kieserite, to offset the losses of $92.1 \text{ kg N ha}^{-1}$, 6.8 kg P ha^{-1} , 7.9 kg K ha^{-1} , $98.2 \text{ kg Ca ha}^{-1}$, and $27.7 \text{ kg Mg ha}^{-1}$ (Table A.1, Appendix A), respectively. In our study, additions of N and P due to pine straw-associated fertilizations (223 kg ha^{-1} of N and 64 kg ha^{-1} of P per application) largely exceed the removals expected in all pine straw management scenarios (see N and P removals on Fig. 1). However, these N and P fertilization rates are typical operational recommendations used to enhance forest growth and leaf area production (Jokela et al., 2004).

5. Conclusions

Results from this study suggested that pine straw raking was an economically attractive option for forest landowners that desired to diversify their management objectives and income sources from traditional products (e.g., pulpwood, sawtimber) with slash pine. Landowners were also financially better off when forestlands were intensively managed for pine straw raking, especially without the risk of fire. However, intensively managed and raked stands had greater nutrient removals.

¹⁵ It is also noteworthy to mention that forest landowners should undertake pine straw raking on soils with low risk of erosion potential, for example, flatwoods and upland sites with slopes less than 2% and 8%, to ensure a sustainable forest management (Morris et al., 1992).

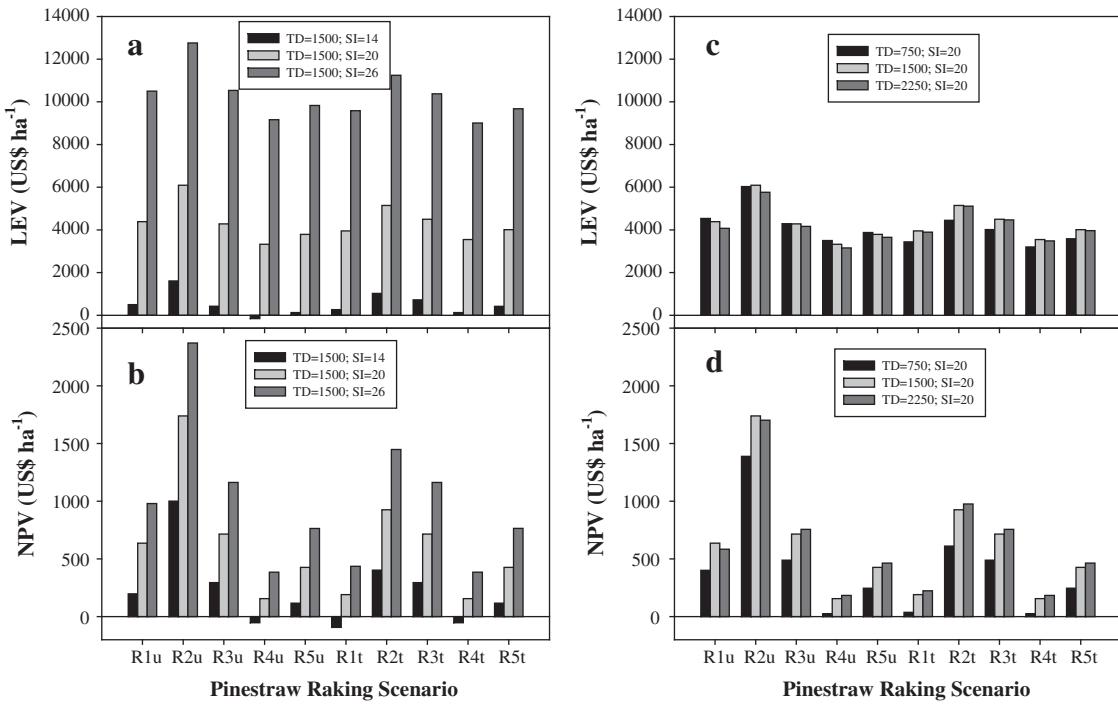


Fig. 2. LEV (a,c), NPVr (b,d) with different SI/TD combinations for all raking scenarios in slash pine stands in the southeastern United States. SI and TD in m and trees ha⁻¹, respectively. LEV and NPVr based on $t_o = 0$. LEV and NPVr for $t_o = 1$ available from authors upon request.

Carbon and nutrient removals were also greater when raking was undertaken in stands having a higher site index because of more significant pinestraw yields in such stands. Although evidence in the U.S. is not conclusive, it is expected that C and nutrient removals could cause

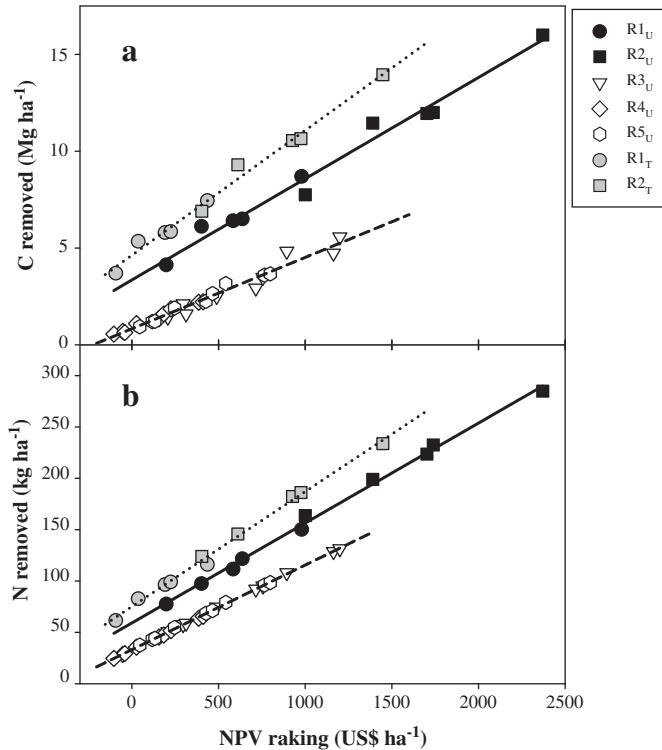


Fig. 3. Relationship between NPVr and removal of C (a) and N (b) for different pinestraw raking scenarios on slash pine stands in the southeastern United States.

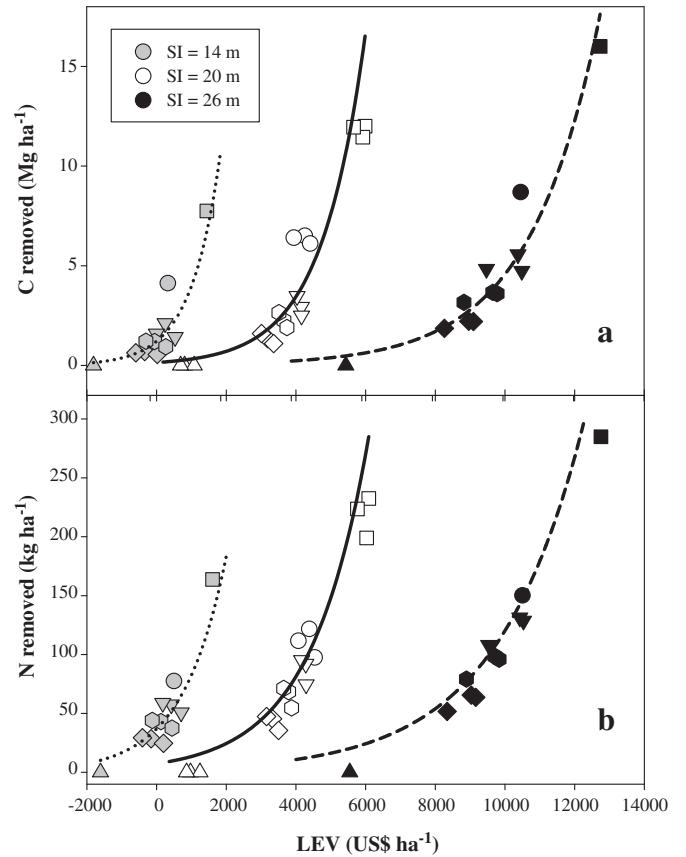


Fig. 4. Relationship between LEV and removal of C (a) and N (b) due to pinestraw raking for unthinned slash pine stands with different SI. An exponential curve was fitted to all pinestraw raking scenarios in each SI group. Symbols representing pinestraw raking scenarios are the same described in Fig. 3.

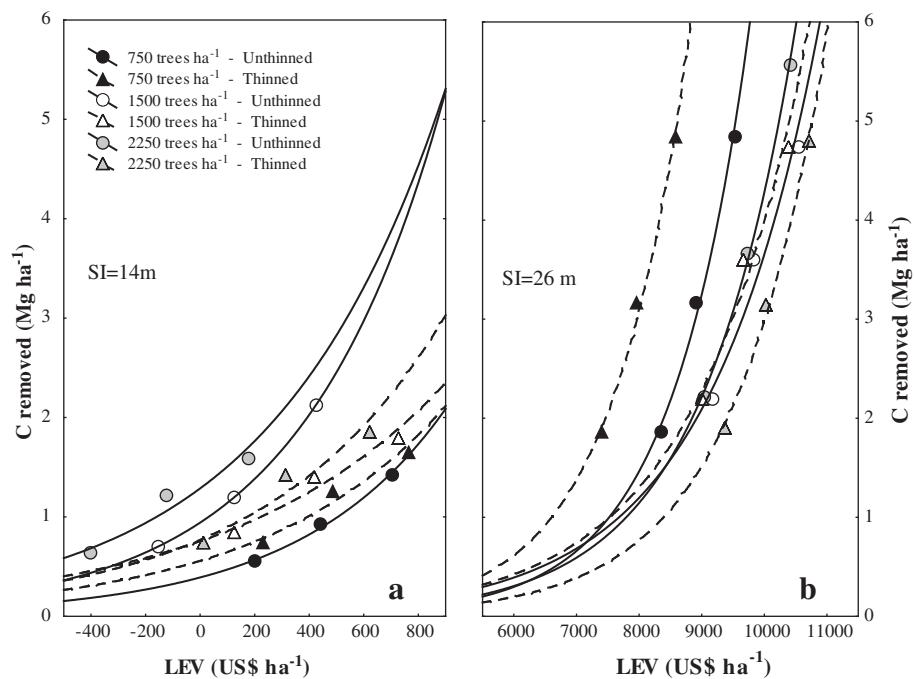


Fig. 5. Relationship between LEV and removal of C due to pinestraw raking before age 15 (R3, R4 and R5) in slash pine stands with different planting densities and thinning regimes, for stands with SI = 14 m (a) and SI = 26 m (b). An exponential curve was fitted to all pinestraw raking scenarios in each planting density and thinning regime group.

decreases in forest stand productivity in the long term. On the other hand, it has been well established in the southeastern U.S. that many soils that support slash pine plantations have low inherent fertility and they are responsive to fertilizer additions (Fox et al., 2007; Jokela et al., 1989; Vogel and Jokela, 2011; Pritchett and Comerford, 1982). Thus, fertilization may be an option to compensate for future potential declines in forest productivity. Yet, ameliorative fertilizer additions would not necessarily compensate for possible changes in soil organic matter levels and the associated effects on other soil physical, chemical and microbiological properties.

Landowners might also be encouraged to extensively manage their forestlands for pinestraw raking due to similar economic revenues and shorter rotation ages to intensive pinestraw management. Slash pine stands managed extensively for pinestraw raking were generally more efficient in terms of nutrient removal with respect to economic returns. Planting sites with high potential productivity (SI) are recommended since landowners would be economically better off for similar levels of nutrient removals.

Decisions regarding planting density would depend on the quality of the site. Forest landowners should plant less/more trees for high/low productive sites. Fertilization and weed control treatments, coupled with the use of genetically improved seedling stock, would be needed to increase the overall productivity and yield of pinestraw from the site.

Volatility in prices and different people's perceptions are also factors that might negatively affect pinestraw markets. With a growing interest in diversifying the sustainable supply of forest products, future research should focus on pinestraw removal experiments to quantify the effects on long-term site productivity. Thus, growth and yield of a forest stand could be stochastically modeled as a function of endogenous risk associated with potential reductions in stand productivity. Another option might be to develop a probability function for forest stand productivity under different scenarios of pinestraw raking. Regardless of the approach, a potential decline in forest productivity may lead to a decrease in the estimates of profitability of forestlands. This information would be essential to determine sustainable forest management strategies to mitigate any

Appendix A

Table A.1

LEV and NPV_r, rotation age (R), number of rakings (N), and all nutrient removals at different levels of risk for all scenarios (Sc).

Sc ^a	t _o	LEV US\$ ha ⁻¹	R years	N	NPV _r US\$ ha ⁻¹	C Mg ha ⁻¹	N kg ha ⁻¹	P	K	Ca	Mg
NR _u	1	975	20	—	—	—	—	—	—	—	—
R1 _u	0	4386	26	10	637	6.5	121.7	8.9	10.5	129.8	36.6
R1 _u	1	2340	22	8	367	6.2	96.8	7.1	8.3	103.2	29.1
R2 _u	0	6091	26	19	1739	12.0	232.5	17.1	20.0	247.8	69.9
R2 _u	1	3902	23	16	1200	11.6	195.1	14.3	16.7	208.0	58.6

Table A.1 (continued)

Sc ^a	t ₀	LEV US\$ha ⁻¹	R years	N	NPV _r US\$ha ⁻¹	C Mg ha ⁻¹	N kg ha ⁻¹	P	K	Ca	Mg
							kg ha ⁻¹				
R3 _u	0	4283	22	8	715	2.9	92.1	6.8	7.9	98.2	27.7
R3 _u	1	2803	19	8	635	4.6	92.1	6.8	7.9	98.2	27.7
R4 _u	0	3328	22	4	156	1.3	45.4	3.3	3.9	48.4	13.6
R4 _u	1	1753	20	4	134	1.8	45.4	3.3	3.9	48.4	13.6
R5 _u	0	3792	22	6	427	2.2	68.5	5.0	5.9	73.0	20.6
R5 _u	1	2254	19	6	377	3.5	68.5	5.0	5.9	73.0	20.6
NR _t	1	1248	21	—	—	—	—	—	—	—	—
R1 _t	0	3955	24	9	191	5.8	96.6	7.1	8.3	103.0	29.0
R1 _t	1	2091	22	8	123	5.5	84.2	6.2	7.2	89.7	25.3
R2 _t	0	5146	24	17	926	10.5	182.3	13.4	15.6	194.3	54.8
R2 _t	1	3282	22	15	778	9.8	157.4	11.6	13.5	167.8	47.3
R3 _t	0	4501	22	8	715	2.9	92.1	6.8	7.9	98.2	27.7
R3 _t	1	2994	20	8	635	4.0	92.1	6.8	7.9	98.2	27.7
R4 _t	0	3547	22	4	156	1.3	45.4	3.3	3.9	48.4	13.6
R4 _t	1	1960	20	4	137	1.8	45.4	3.3	3.9	48.4	13.6
R5 _t	0	4010	22	6	427	2.2	68.5	5.0	5.9	73.0	20.6
R5 _t	1	2457	20	6	377	3.0	68.5	5.0	5.9	73.0	20.6

^a Subscripts u and t reflect unthinned and thinned pine straw raking scenarios, respectively.

losses in future productivity. Incorporation of biodiversity values in the economic analysis is also a subject of further research.

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