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Review

Pine Straw Raking and Growth of Southern Pine: Review and Recommendations

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Abstract: Pine straw, the uppermost forest floor layer of undecayed, reddish-brown pine needles, is raked, baled, and sold as a landscaping mulch throughout the southeastern United States. Loblolly (*Pinus taeda,* L.), longleaf (*P. palustris,* Mill.), and slash (*P. elliottii* Engelm. var. *elliottii*) pine are the three southern pine species commonly raked for pine straw. The value of pine straw as a forest product is large. Private landowner pine straw revenues have steadily increased throughout the southeastern United States over the past two decades and now total more than USD 200 million. Information is limited on the short- or long-term effects of pine straw removal on foliage production or stand growth in southern pine stands. Results from most published studies suggest that annual pine straw raking without fertilization on non-old-field sites reduces straw yields compared to no raking. Old-field sites often do not benefit from fertilization with increased pine straw or wood volume yields. Though fertilization may be beneficial for pine straw production on some sites, understory vegetation presence and disease prevalence may increase following fertilization. This review addresses pine straw removal effects on pine straw production and stand growth parameters based on recent studies and provides fertilization recommendations to maintain or improve pine straw production and stand growth and yield.

Keywords: pine straw; raking; fertilization; longleaf pine; slash pine; loblolly pine

1. Introduction

Pine straw, the uppermost forest floor layer of recently fallen undecayed reddish-brown pine needles, is raked, baled, and sold as a landscaping mulch throughout the United States. Loblolly pine (*Pinus taeda,* L.), longleaf pine (*P. palustris,* Mill.), and slash pine (*P. elliottii* Engelm. var. *elliottii*) are the three southern pine species commonly raked for pine straw with the order of preference being longleaf, slash, then loblolly straw [1]. Longer needle length, better color retention, and slower rate of deterioration are factors for this order of preference. Pines shed most needles during the fall, but spring and summer droughts can cause needles to start shedding in late spring through the summer months [2,3].

The value of pine straw as a forest product is large. Forest landowners in Georgia received USD 15.5, USD 17.5, and USD 22.4 million in pine straw revenues in 2000, 2001, and 2002, respectively [4] with recent annual revenue estimates of USD 56 million in 2013 rising to USD 80.6 million in 2018 [5]. The most recent data for Florida reported annual revenue estimates of USD 79 million [6]. Pine straw harvesting in North Carolina has been estimated to be a USD 34.8 million annual industry [7], while in South Carolina estimated annual revenues were USD 11 million as of 2015 [8]. Pine straw revenue data for other Southeastern states are not readily available, but conservatively, annual pine straw revenues in the southeastern United States total over USD 200 million USD. Since 2005 in the southeastern United States, pine chip-n-saw and sawtimber stumpage prices have decreased from USD 23.58 and USD 39.91 t^{-1} to USD 15.42 and USD 21.77 t^{-1}, respectively as of fourth quarter 2019 [9,10]. Pine straw revenues have helped many landowners maintain reasonable cash flows to achieve attractive rates of return on their forestland [11]. Internal rates of return can be increased from 5.5 to 9.8% without pine straw production to 8.8 to 16.2% with annual pine straw income in loblolly and slash pine stands [12]. Land expectation value (LEV) can be increased by 230% or more in longleaf stands with pine straw and timber revenues compared to timber revenues alone for 60 to 120-year rotation ages [13].

Pine straw can be sold by the bale or by the hectare. During the early 2000s, per hectare reported prices in Georgia ranged from USD 86.48 to USD 222.39 ha^{-1} for each raking [14]. More recently, 2018 Georgia state-wide estimated pine straw per hectare revenues were USD 345.94 ha^{-1} [5]. Revenue as high as 716.59 ha^{-1} y^{-1} have been reported for high- quality longleaf pine stands with multiple raking opportunities [15]. Annual per hectare prices in 2019 and 2020 for old field planted, unthinned longleaf stands ranged from USD 494.20 to USD 864.85 ha^{-1} in Georgia [16]. Pine straw can also be sold by the bale with longleaf pine receiving the highest price per bale, followed by slash, then loblolly pine.

When use of pine straw for landscaping first began gaining popularity in the 1960s and 1970s, the portions of stands that were raked had understory vegetation and woody debris cover, causing irregularities in raking coverage and operation intervals. More recently, crews and pine straw contractors have begun to manage loblolly, longleaf, and slash pine stands employing herbicides, mowing, chipping, piling or burning at least two to three years prior to raking to remove understory vegetation; clear downed, woody debris; and facilitate raking over the majority of the site. A stand, depending on growth rate, species, and stocking may first be raked between 5 and 12 years old, usually at or soon after canopy closure. The first raking can often produce between 247 and 1087 bales ha^{-1} [17–19] depending on site productivity, species, stocking, age, percent rakeable area in a stand, and raking intensity assuming a common rectangular bale size of 33 × 33 × 70 cm. The raking of pine stands generally occurs annually. Other raking regimes include semi-annual to once every 2– 5 years.

Pine straw estimates from litterfall traps are well correlated to stand basal area [17], but the relationship between pine straw yields after raking and stand basal area are poor [17,20]. On average, 75% of a pine stand's area could be raked operationally in the 1980s to early 1990s [17], though the percentage of rakeable stand area has increased over the past two decades.

There are considerable concerns that annual or more frequent pine straw raking can reduce stand growth. Nutrient removals from frequent raking exceed removals associated with normal pulp and sawtimber harvesting and may induce nutrient deficiencies [17]. Intensive, frequent raking can also displace and accelerate decomposition of the lower (fermentation or Oe and humus Oa) forest floor layers [15]. These lower two forest floor layers may be important in reducing evaporative losses [21]. Fertilization may balance nutrient removals lost to straw raking, but it is not clear whether there is an overall positive growth response to fertilization when combined with pine straw raking. Until recently, few studies on the effects of pine straw removal on the growth and performance of southern pine stands have been conducted. Notable exceptions were two studies of straw removal on sandy soils in South Carolina, USA [21,22]. However, during the last three decades eleven studies on pine straw removal have been completed. In this paper, we review eleven studies on the effects of pine straw raking on soil moisture, pine stand growth, and straw production and provide fertilization recommendations for raked stands to maintain or enhance pine straw production and tree growth. These studies were conducted with loblolly, slash, and longleaf pine on sites with a variety of soil types, land use histories, and management regimes such as unthinned vs. thinned stands.

2. Effects of Raking on Stand Growth, Pine Straw Production, and Water Stress

2.1. Longleaf Pine

Five studies (two post-thinning continued studies of unthinned stands) on longleaf pine straw production, growth response, or soil moisture stress due to pine straw raking, pine straw raking with fertilization, or pine straw production with fertilization are presented in Tables 1–5 and Figures 1–6. McLeod et al. [22] conducted a study at the Savannah River Site in Aiken County, South Carolina in three 12-year-old longleaf pine stands on Fuquay soil (loamy Arenic Plinthic Kandiudults), Gunter soil (loamy, siliceous, semiactive, thermic Grossarenic Plinthic Paleudults) and Troup soil (loamy, kaolinitic, thermic Grossarenic Kandiudults). This study investigated the potential impact of pine straw removal on macronutrient cycling. Their results differed among soils. A significant (Tukey's test at the 5% alpha level) reduction in pine diameter growth occurred on the Fuquay and Troup soils with the removal of either the litter layer (Oi) or the litter plus fermentation layers (Oi + Oe) in the first (Troup) the first and second (Fuquay) year after treatment. Diameter growth two years after treatment on the Troup and three years after treatment on the Fuquay was not significantly different between the no rake and rake treatments. Foliar nitrogen (N) and phosphorus (P) did not differ between the rake and no rake plots across the three soil types. Pine straw biomass was reduced on raked plots by 22, 27, and 32% on the Gunter, Fuquay, and Troup (statistically significant) soils (Figure 1), respectively, leading McLeod et al. [22] to conclude that the overall effect of litter removal is a reduction in the standing crop of macronutrients due to litter biomass reductions (Figure 2). The authors also concluded that there was a reduction in total litter biomass for at least three years following litter raking. Diameter growth reductions on the Fuquay and Troup soils were most pronounced in the first year following litter raking, which according to McLeod et al. [22] "suggests rapid modification of an environmental parameter which controls growth". They surmised that the most feasible explanation was the disruption of the hydrologic cycle. This would occur in two ways: (1) "drying most actively decomposing litter with removal of the Oi layer affected nutrient release", and (2) "removal of the litter might allow greater evaporation from the soil and consequently water stress the trees" [22].

Table 1. Longleaf pine study descriptions from sites throughout the southeastern United States and the effects of pine straw raking and fertilization on longleaf pine stand parameters.

Reference, Statistical Test, Alpha Level	State/Soils/ Stand Age (Years)	Treatments [1]	Initial Trees ha^{-1} (Basal Area m^2 ha^{-1}) by Soil Series	Stand Parameter, Treatment	Effect on Stand Parameter
[22] ANOVA, Tukey, 5% alpha level	South Carolina Fuquay, Gunter, Troup (Age 16–19)	NR, R, ROiea	Fuquay NR = 1410 (38.1) R = 1319 (26.9) ROiea = 1233 (26.9) Gunter NR = 1069 (25.0) R = 538 (15.1) ROiea = 1519 (32.8) Troup NR = 1089 (24.7), R = 1129.2 (25.7) ROiea = 1151 (25.5)	Diameter increment	Significant diameter increment reduction in Oi and Oiea rake plots on Troup and Fuquay soils 1- and 2-years post treatment, respectively.
[21] ANOVA, Tukey, 5% alpha level	South Carolina Troup (Age 19)	Same as [22]	Same as [22]	Soil moisture @ 0–30 cm, 30–60 cm, 60–90 cm Xylem pressure potential (XPP) Estimated hours day^{-1} of impaired photosynthesis	Soil moisture was consistently lower in rake Oi and rake Oiea plots than no rake @ all depths After raking, days 12 to 49 trees in R Oi and R Oiea had lower XPP 6.2 h NR 6.4 h R Oi 7.9 h R Oiea

[1] Treatments: no raking, no fertilization (NR, NF), rake litter layer (Oi) only, no fertilization (R, NF), no raking, fertilize (NR, F) (see study for fertilization details), rake Oi only, fertilize (R, F), rake Oi only at 3-year intervals (R3), rake all forest floor (ROiea) (litter layer (Oi), litter + fermentation + humus layers (Oiea)).

Table 2. Longleaf pine study descriptions from sites throughout the southeastern United States and the effects of pine straw raking and fertilization on longleaf pine stand parameters.

Reference, Statistical Test, Alpha Level	State/Soils/ Stand Age (Years)	Treatments [1]	Initial Trees ha^{-1} (Basal Area ha^{-1}, m^2) by Soil Series	Stand Parameter, Treatment	Effect on Stand Parameter
[15,23] ANOVA, non-orthogonal linear contrasts, 15% alpha level	Louisiana Ruston Smithdale (Age 36 to 42)	NR, NF; R, NF; NR, F; R, F; 50.4 kg N + 55.8 kg P applied at age 36	NR, NF = 817 (19.5) R, NF = 736 (19.9) NR, F = 736 (19.3) R, F = 805 (19.5)	R vs. NR, NF 3 years after treatment	R, NF plots grew 1.0 m^2 ha^{-1} BA and 29.8 m^2 ha^{-1} vol. less than NR, NF
				R, F vs. R, NF	R, F increased volume by 18.2 m^3 ha^{-1} over R, NF
[24] ANOVA, Tukey, 5% alpha level	South Carolina Fuquay (Age 30)	NR, NF; R3, NF NR, F R3,F 45.4 kg N + 4.5 kg P applied at age 30	NR, NF = (39.0) NR, F = (29.2) R3,NF = (26.2) R3,F = (23.7) R3Oiea,NF = (33.2) R3Oiea,F = (29.3)	Fertilization vs. no fertilization effect on Oi dry weight ha^{-1}	NR, F increased Oi weight by 1662.2 kg ha^{-1} over R, NF R3, F increased Oi weight by 1271.1 kg ha^{-1} over R3,NF R3Oiea, F increased Oi weight by 728.5 kg ha^{-1} over R3Oiea,NF
[19,25] ANOVA, Duncan's Multiple Range test, 5% alpha level	South Carolina Alpin (Age 9–13 and 32–36)	NR, NF; NR, F; 68 kg N, 72.9 kg P, 233.0 kg K at study initiation	Age 9: NR, NF = 1171 (5.5) NR, F = 1373 (5.5) Age 32: NR, NF = 484.3 (15.8) NR, F = 437.4 (15.2)	NR, F vs. NR, NF effect on Oi, BA and volume ha^{-1}	NR, F increased pine straw production by 3110.2 to 4623.5 kg ha^{-1}, basal area ha^{-1} by 52 to 67% and volume ha^{-1} by 8.7 to 11.2 m^3 ha^{-1} over 4 years over NR, NF

[1] Treatments: no raking, no fertilization (NR, NF), rake Oi only, no fertilization (R, NF), no raking, fertilize (NR, F) (see study for fertilization details), rake Oi only, fertilize (R, F), rake Oi only at 3-year intervals (R3), rake all forest floor (ROiea) (litter layer (Oi), litter + fermentation + humus layers (Oiea)).

Table 3. Longleaf pine study descriptions from sites throughout the southeastern United States and the effects of pine straw raking and fertilization on longleaf pine stand parameters.

Reference, Statistical Test, Alpha Level	State/Soils/ Stand Age (Years)	Treatments [1]	Initial Trees ha^{-1} (Basal Area ha^{-1}, m^2) by Soil Series	Stand Parameter, Treatment	Effect on Stand Parameter
[26] ANOVA Tukey 5% alpha level	South Carolina Fuquay (Ages 45–51) post-thinning	NR, NF; NR, F; R, NF; R, F; Riea, NF; Riea, F; 135.4 kg ha^{-1} N + 35.9 kg ha^{-1} P at three year intervals at ages 44, 47, and 50	Age 41: All treatments (20.7)	NR, R and NF, F effects on annual litterfall production	One- and two-years post-fertilization annual litterfall was significantly greater for the NR, F (4467 kg ha^{-1}) vs. the R, NF (2442 kg ha^{-1}) treatment, all other treatments and time since burning statistically similar for annual litterfall
[27] ANOVA, orthogonal linear contrasts, 5% alpha level	Louisiana Ruston Smithdale (Age 46–50) post-thinning	NR, NF; R, NF; NR, F; R, F; 56 kg ha^{-1} P + 80.7 kg ha^{-1} K at age 48	Age 43: All treatments 168 (14.7)	Oi F vs. NF 2 years after treatment; basal area and volume ha^{-1}	No significant gain in pine straw production with fertilization observed in three of four assessments; no significant basal area or volume improvements detected

[1] Treatments: no raking, no fertilization (NR, NF), rake Oi only, no fertilization (R, NF), no raking, fertilize (NR, F) (see study for fertilization details), rake Oi only, fertilize (R, F), rake Oi only at 3-year intervals (R3), rake all forest floor (ROiea) (litter layer (Oi), litter + fermentation + humus layers (Oiea)).

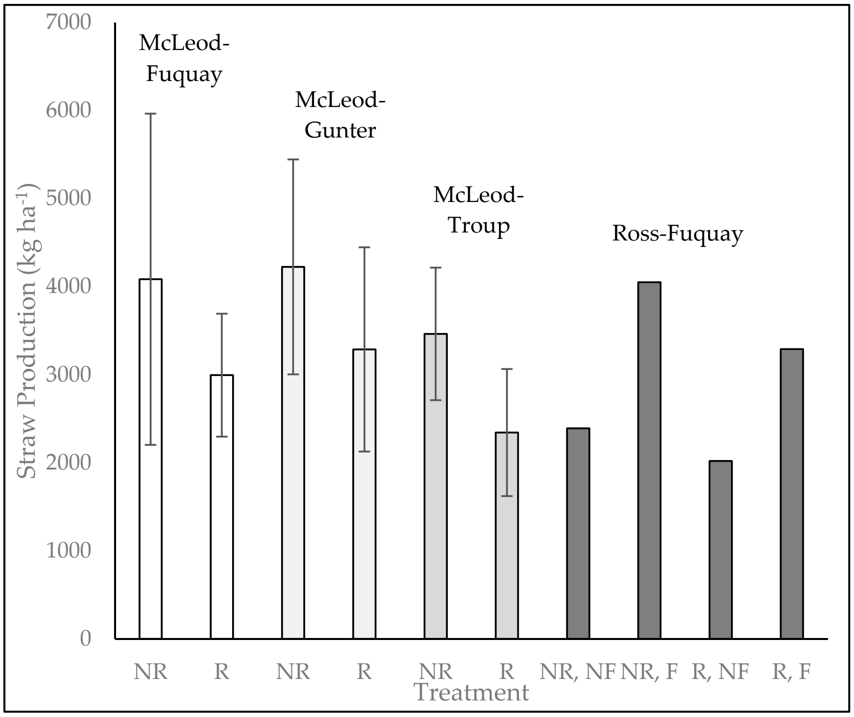

Figure 1. Longleaf pine mean annual pine straw production (± standard deviation) two (Troup soil) and three (Fuquay and Gunter soils) years after treatment [22] or on a three-year raking regime after seven years [24]. Standard deviations were not reported for [24]. Treatments: no rake, no fertilization (NR, NF); rake, no fertilization (R, NF); no rake, fertilization (NR, F); rake, fertilize (R, F) (refer to Tables 1 and 4 for study details, information on fertilizer treatments, and statistical test results).

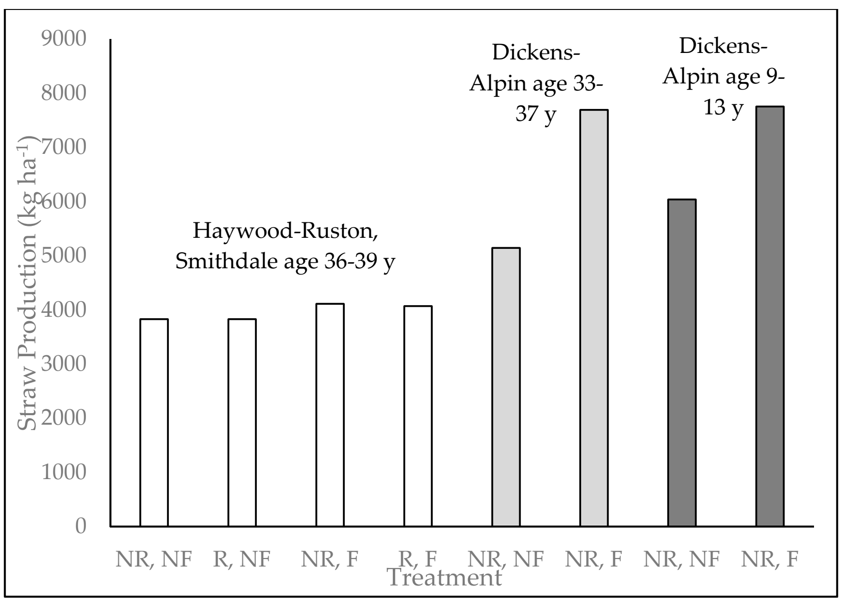

Figure 2. Longleaf pine mean annual litterfall [15] or pine straw production over the study period by treatment [19]. Treatments: no rake, no fertilization (NR, NF); rake, no fertilization (R, NF); no rake, fertilization (NR, F); rake, fertilize (R, F) (refer to Tables 2 and 4 for study details, information on fertilizer treatments, and statistical test results).

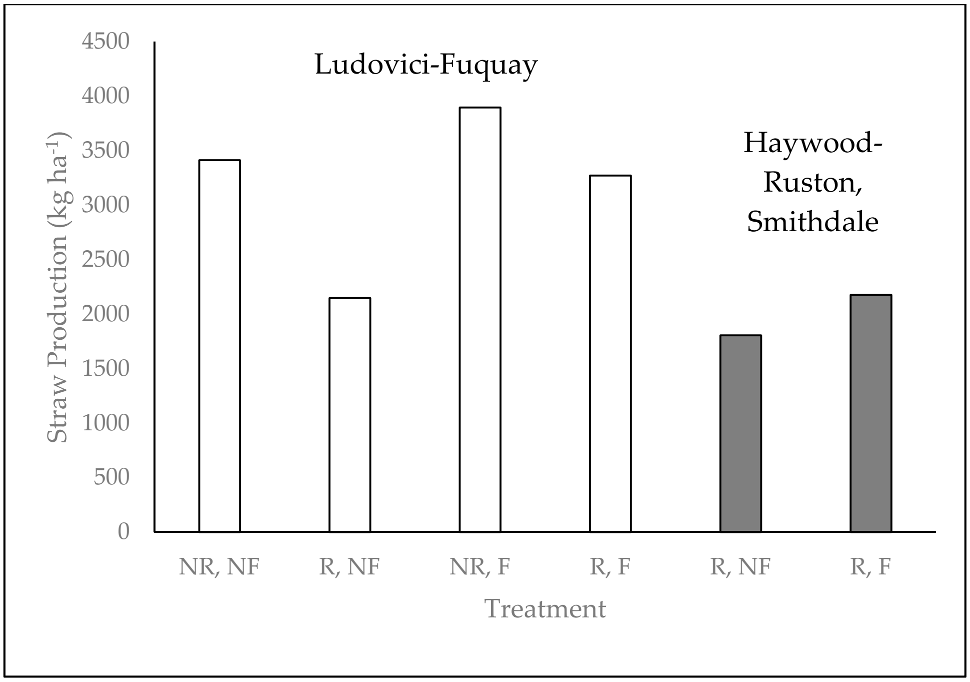

Figure 3. Post-thinning mean annual pine straw production [26] or litterfall over the study period by treatment [27]. Treatments: no rake, no fertilization (NR, NF); rake, no fertilization (R, NF); no rake, fertilization (NR, F); rake, fertilize (R, F) (refer to Tables 3 and 4 for study details, information on fertilizer treatments, and statistical test results).

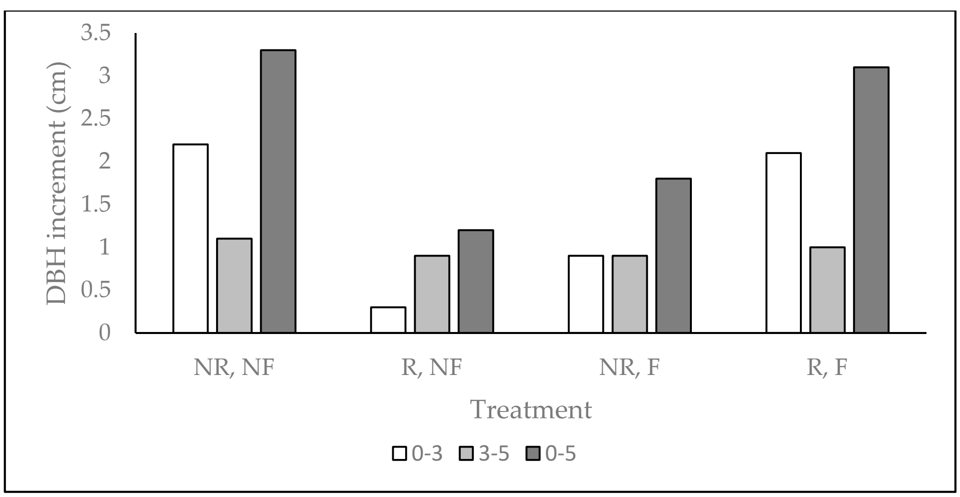

Figure 4. Longleaf pine (stand age 34–39) diameter at 137 cm above groundline (dbh) increment by treatment 0 to 3 years after treatment (YAT), 3 to 5 YAT and over the entire five-year study period [15].

On a similar Savannah River site, Ginter et al. [21] investigated the impact of pine straw raking on the hydrologic cycle of a planted 19-year-old longleaf pine stand established on an old field site with Troup soils. Soil moisture and xylem water potential were measured for seven weeks after removal of only the litter layer (Oi), removal of all organic forest floor layers (Oi+Oe+Oa), and a no-removal control. They found that two weeks following raking, xylem pressure potential in the control, Oi layer-only and complete forest floor removal plots were significantly different (Tukey's test at the 1% alpha level). Trees in plots which had all of the O horizon removed had the lowest xylem pressure potential (and were the most stressed, 2–5 bar less than control during weeks two through seven after treatment). Trees in the Oi-only removed plots had intermediate xylem pressure (1–3 bars less than the control during weeks two through seven after treatment). Trees in the control plots had the highest xylem pressure potential (were least stressed, 15–28 bars during study period). This pattern was consistent throughout the seven-week study period and was correlated with measured soil moisture. The authors concluded that complete O horizon removal, and to a lesser extent litter layer removal, was detrimental to tree diameter growth on this and similar low water holding capacity soils. Together, the McLeod et al. [22] and Ginter et al. [21] studies indicated that near-term (one to three years after treatment) longleaf pine growth reductions from raking may be more related to water stress on these droughty sands than to nutrient effects.

A study by Ross et al. [24] also evaluated the effect of partial (Oi) and complete (Oi+Oe+Oa) forest floor removal in longleaf stands (Fuquay soil) on the Savannah River Site in Aiken County, South Carolina. In addition to pine straw removal at three-year intervals, they included a single fertilizer application (with and without 112.2 kg N + 11.2 kg elemental P ha^{-1} applied prior to raking. In contrast to the results of McLeod et al. [22], where no fertilizer was applied, Ross et al. [24] found that fertilization and raking on three-year intervals had no adverse effect on tree growth during the seven-year study. Fertilization increased longleaf pine straw production by 75% (non-significant) but had no measurable effect on tree growth. Fertilization also increased forest floor nutrient weights by 85% for N, 236% for P, 43% for Ca, and 57% for Mg.

Table 4. Summarization of statistically significant longleaf pine straw and litter production results by treatment, soil series, and study. Non-significant (NS), '* (-)' and '* (+)' indicate either a negative or positive response associated with significant variables (*), and '—' indicates that a statistical test was not reported for that variable and treatment combination.

				Treatment			
Species	**Study Reference**	**Soil Series**	**Variable**	**Raking**	**Fertilizer**	**Raking × Fertilization**	**Comments**
Longleaf	[22]	Fuquay	Annual pine straw production	NS	–	–	
Longleaf	[22]	Gunter	Annual pine straw production	NS	–	–	
Longleaf	[22]	Troup	Annual pine straw production	* (-)	–	–	Straw production significantly less in raked compared to control treatment.
Longleaf	[24]	Fuquay	Annual pine straw production	NS	NS	NS	Straw production increased 75% due to fertilization; high variability noted.
Longleaf	[15]	Ruston and Smithdale	Annual pine straw production	NS	NS	NS	High variability by year in straw production noted.
Longleaf	[19]	Alpin	Annual pine straw production	–	–	–	Straw production peaked three years after fertilization.
Longleaf	[26]	Fuquay	Straw production post-thinning	* (-)	* (+)	NS	Results were significantly different for litter production two of five years.
Longleaf	[27]	Ruston and Smithdale	Straw production post-thinning	* (-)	* (+)	–	Fertilization significantly improved pine straw yields over raking alone one of four years.

Table 5. Summarization statistical test results for longleaf pine growth and yield variables by treatment, soil series, and study. Non-significant (NS), '* (-)' and '* (+)' indicates either a negative or positive response associated with significant variables (*), and '—' indicates that a statistical test was not reported for that variable and treatment combination.

				Treatment			
Species	**Study Reference**	**Soil Series**	**Variable**	**Raking**	**Fertilizer**	**Raking × Fertilization**	**Comments**
Longleaf	[15]	Ruston and Smithdale	dbh five-year increment	NS	NS	NS	
Longleaf	[15]	Ruston and Smithdale	Annual basal area increment	NS	NS	NS	Fertilization significant one of three years
Longleaf	[15]	Ruston and Smithdale	Annual volume increment	NS	NS	NS	Fertilization significant one of three years
Longleaf	[24]	Fuquay	Annual basal area increment	NS	NS	NS	
Longleaf	[19]	Alpin	Annual basal area increment	–	–	–	No statistical test reported
Longleaf	[19]	Alpin	Annual volume increment	–	–	–	No statistical test reported
Longleaf	[26]	Fuquay	Three-year dbh increment	* (-)	NS	NS	Annual raking significantly reduced dbh increment three of nine years.
Longleaf	[26]	Fuquay	Three-year height increment post-thinning	NS	* (+)	NS	Fertilization improved height increment for three out of nine years
Longleaf	[26]	Fuquay	Three-year basal area increment post-thinning	NS	NS	NS	
Longleaf	[27]	Ruston and Smithdale	Six-year basal area increment post	NS	NS	NS	Fertilization completed four years after thinning
Longleaf	[27]	Ruston and Smithdale	Six-year volume increment	NS	NS	NS	Fertilization completed four years after thinning

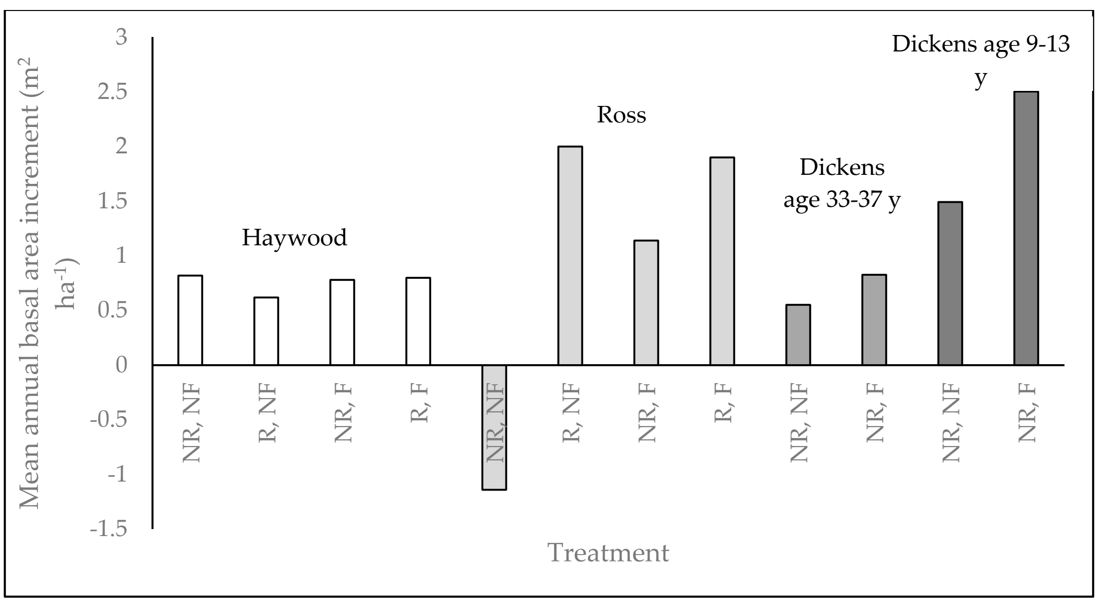

Figure 5. Longleaf pine mean annual basal area increment by treatment [15,19,24]. Treatments: no rake, no fertilization (NR, NF); rake, no fertilization (R, NF); no rake, fertilization (NR, F); rake, fertilize (R, F) (refer to Tables 2 and 5 for study details, information on fertilizer treatments, and statistical test results).

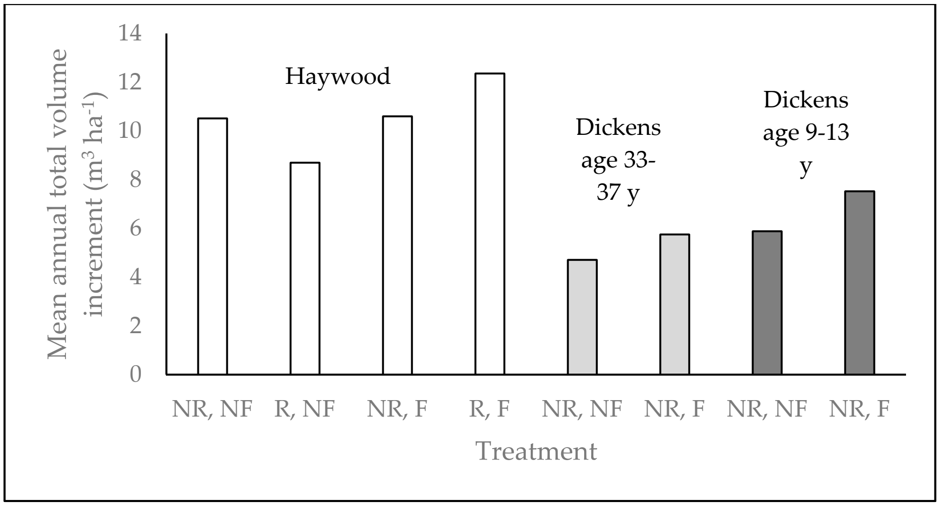

Figure 6. Longleaf pine mean annual volume ha growth by treatment [15,19,25]. Treatments: no rake, no fertilization (NR, NF); rake, no fertilization (R, NF); no rake, fertilization (NR, F); rake, fertilize (R, F) (refer to Tables 2 and 5 for study details, information on fertilizer treatments, and statistical test results).

Studies by Haywood et al. [15,23] conducted experimental pine straw raking with and without 50.5 kg N and 56.1 kg elemental-P ha^{-1} as diammonium phosphate (18-46-0, DAP) fertilization applied prior to raking treatments (March 1991) in a 37-year-old longleaf pine stand in Rapides Parish, Louisiana. The soils were Ruston (fine-loamy, siliceous, subactive, thermic Typic Hapludult) and Smithdale series (fine-loamy, siliceous, semiactive thermic Typic Paleudult). The application of diammonium phosphate at 280.5 kg ha^{-1} did not significantly (non-orthogonal linear contrasts at the 15% alpha level) increase longleaf pine diameter, height basal area, or volume growth three and five years post-treatment (Table 5). They found no significant gain in pine straw production with 280.5 kg ha^{-1} one, two, and four years after fertilization. A significant increase in foliar P levels in the fertilized vs. the unfertilized plots was observed three years after treatment. Available soil P was significantly greater (15.4 vs. 0.81 ppm) in the DAP-fertilized vs. unfertilized plots two years after treatment. Soil and foliar potassium (K) were considered to be deficient with all treatments.

Five-year basal area increment was greatest in the no rake, no fertilizer treatment (4.1 m^2 ha^{-1}), followed by the rake annually, fertilize (4.0 m^2 ha^{-1}), the no rake, fertilize (3.5 m^2 ha^{-1}), and the rake annually, no fertilizer (3.1 m^2 ha^{-1}). Diameter increment for Haywood et al. [15] followed a similar trend as reported by Dickens [19] with the largest growth loss occurring early in the study for the rake annually, no fertilization treatment. Results reported by Haywood et al. [15] noted that diameter at 137 cm above groundline (dbh) increment for the rake annually, no fertilization treatment was 2.5 mm three years after treatment., The dbh increments for other treatments were 12.7 mm (no raking, fertilize), 20.3 mm (no rake, no fertilization), and 22.9 mm (rake and fertilize), three years after treatment (Figure 3). Diameter increments three to five years after treatment were 7.6 mm (rake and fertilize) or 10.2 mm (no rake, no fertilization, no raking, fertilize, and rake annually, no fertilization). The unraked, unfertilized and raked annually, fertilized treatments had a 17.8 mm greater dbh increment five years after treatment than the raked, unfertilized plots (Figure 3). Five year volume ha^{-1} increment was greatest for the rake annually, fertilize (61.7 m^3 ha^{-1}), followed by the no rake, no fertilizer (52.6 m^3 ha^{-1}), no rake, fertilize (46.0 m^3 ha^{-1}), and the rake annually, no fertilizer (46.3 m^3 ha^{-1}) treatment. The single application of 280.5 kg DAP ha^{-1} increased litterfall by approximately 280.5 kg ha^{-1} per year between 1991 and 1994 over the unfertilized, raked and unraked plots. Forest floor dry weight for the rake, no fertilization treatment averaged 325.3 kg ha^{-1} per year greater than the rake, fertilization treatment over the four-year pine straw study period. The authors did note that fertilization increased herbaceous vegetation by 59% over unfertilized plots. This understory vegetation increase with NP fertilization may have reduced the rakeable area as was the case in the Ogden and Morris [28] study. Mechanical pine straw harvesting significantly increased soil bulk density in the annually raked plots after three years compared to the unraked plots. Soil bulk density decreased three years after mechanical harvesting ceased to pre-study levels.

Dickens [19,25] also studied longleaf pine growth and pine straw production response following a single NPK dose of 168.2 kg N + 72.9 kg elemental P + 140.2 kg elemental K ha^{-1} during May 1995 in a 9- and 32-year–old longleaf pine stands on Alpin soil series (Thermic, coated Lamellic Quartzipsamments). These soils are considered deep, excessively drained sands with poor fertility. In this case, raking was not performed during the four-year study. Merchantable volume was increased by 28.7 and 36.7 m^2 ha^{-1} in the fertilized compared to the unfertilized treatment four years after treatment in both the younger and older stands, respectively (Table 2). Peak pine straw gains were 1486.4 kg ha^{-1} in year two after NPK fertilization and 2019 kg ha^{-1} in years two and three after fertilization when compared to unfertilized controls in the 9- and 32-year-old stands, respectively. Pine straw production differences began to converge between the fertilized and unfertilized treatments three and four years after application in both stands on this low water and nutrient holding capacity soil.

The Ross et al. [24] and Haywood et al. [15] studies were continued post-thinning to determine if older stands post-thinning respond similarly to raking and fertilization as younger, unthinned stands. Ludovici et al. [26] and Haywood [27] studied the effects of raking and fertilization on stand growth and pine straw production post-thinning. The study by Ludovici et al. [26] included raking (Oi only or Oi+Oe+Oa) and fertilization every three years over a nine-year period post-thinning. Thinning occurred at stand age 42. Every third year, the fertilization treatment was an NP application with 135.4 kg N ha^{-1} plus 35.9 kg P ha^{-1} applied during the winter months. Neither raking nor fertilization had a significant effect on dbh increment, height, or basal area ha^{-1} over the course of nine years, except for dbh increment in response to litter layer raking only (3.6 cm less) compared to the control over the three year period from 1996 to 1999 and fertilization (0.98 m) compared to no fertilization (0.76 m) for height increment during that same period (Table 5). Periodic growth averages were consistently, though not significantly higher in the fertilized treatment as compared to the control. Pine straw litterfall was always greater in the control treatment when compared to litter removal treatments with the same fertilization treatment. Over a five-year period, fertilization increased litter production across treatments by 22 percent. Litter production increases due to fertilization tended to be greatest two years after application [26]. The study by Haywood [27] investigated the effects of raking and fertilization on pine straw production and stand growth post-thinning (age 43). Fertilization was done two years prior to thinning and five years post-thinning. Two-years prior to thinning, the application consisted of 50.5 kg N ha^{-1} and 56.0 kg P ha^{-1} as 280.5 kg ha^{-1} of diammonium phosphate, while the post-thinning application consisted of 56.0 kg P ha^{-1} and 80.8 kg K ha^{-1} as 280.5 kg ha^{-1} of diammonium phosphate and 280.5 kg ha^{-1} of potash. After nearly seven years post-thinning and two years post-fertilization, fertilization had not significantly improved longleaf pine basal area or volume growth as compared to the control (Table 5), while annual raking did not alter stand growth as compared to the control. Pine straw litterfall was not significantly improved over the no fertilizer treatment three of the four years reported in this study. In the year where literfall was significantly greater (312 kg ha^{-1} greater) in the fertilization treatment (Table 4), this occurred prior to the post-thinning fertilizer application and seven years after the pre-thinning fertilizer application [27].

2.2. Loblolly and Slash Pine

Three recent studies have evaluated the effects of pine straw raking and its interaction with fertilization in both loblolly and slash pine (Tables 6 and 7). A study by Ross et al. [24] examined the effects of litter (Oi) layer vs. complete forest floor removal (to mineral soil)on three-year intervals with and without 45.4 kg N + 4.5 kg elemental-P fertilization (pre-raking treatments) in loblolly stands (Fuquay soil (loamy, kaolinitic, Arenic Plinthic Kandiudults) on the Savannah River Site in Aiken County, South Carolina, USA. Fertilization increased loblolly pine straw production by 1189 and 1458 kg ha^{-1} (Figure 7). Fertilization increased litter layer nutrient weights by 43% for N, 179% for P, 109% for K, 25% for Ca, and 21% for Mg (Table 6). There were no significant (Fisher's Protected Least Significant Difference test at the 5% alpha level) treatment effects on loblolly pine basal area growth after seven years (Figure 8).

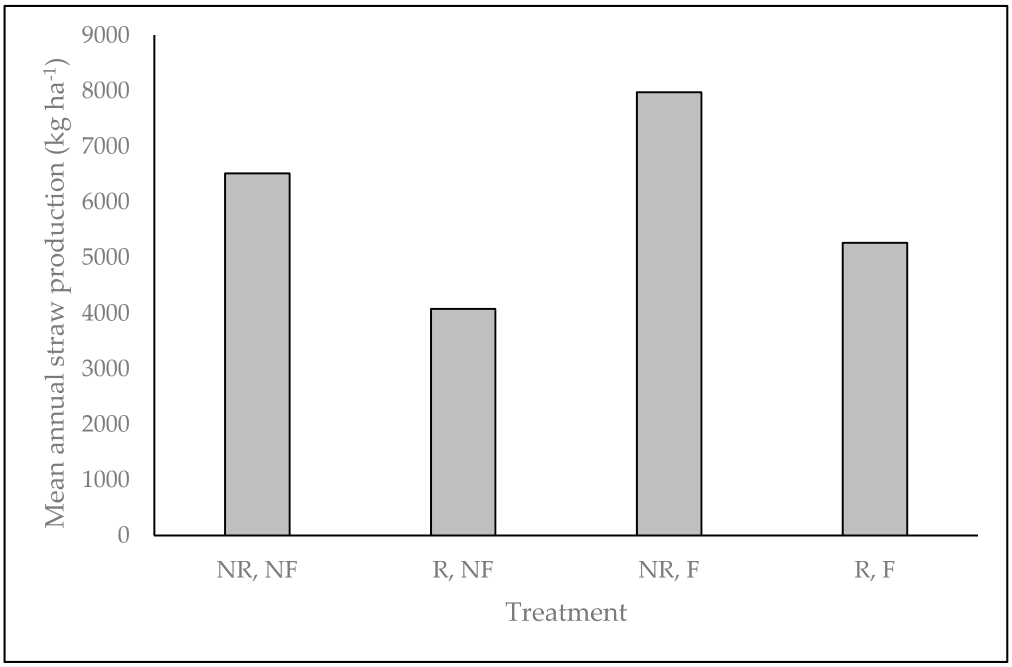

Figure 7. Loblolly pine mean annual pine straw production on a three-year raking regime over the seven year study period by treatment on a Fuquay soil [24]. Treatments: no rake, no fertilization (NR, NF); rake, no fertilization (R, NF); no rake, fertilization (NR, F); rake, fertilize (R, F) (refer to Tables 6 and 7 for study details, information on fertilizer treatments, and statistical test results).

Table 6. Effects of pine straw raking and fertilization on loblolly and slash pine stand parameters.

Reference, statistical Test, Alpha Level	State/Soils Species/Stand Age (Years)	Treatments [1]	Initial Trees ha^{-1} (Basal Area m^2 ha^{-1})	Stand Parameter, Treatment	Effect on Stand Parameter
[24] ANOVA, LSD 5% alpha level	South Carolina Fuquay Loblolly (Age 20)	NR, NF; R3, NF; NR, F; R3, F; 45.4 kg N + 4.5 kg P	NR, NF = (20.4) R3,NF = (23.2) NR, F = (22.3) R3,F = (19.7)	Fertilization vs. no fertilization effect on pine straw production and litter layer (Oi) nutrient weights	Fertilization increased loblolly pine straw production by 1188.1 to 1658.8 kg ha^{-1} and Oi nutrient weights/ac: N 43%, P 279%, K 209%, Ca 25%, and Mg 21%.
[25] General Linear Models procedure	Georgia 1. Rigdon, Olustee 2. Dothan 3. Dothan, Faceville 4. Tifton 5. Dothan, Fuquay Slash and loblolly (Age 12–21)	NR, NF; R, NF; NR, F; R, F; 224.2 kg N, 56.0 kg P, 56.0 kg K at study initiation	Site 1. 1262 (32.4) Site 2. 1312 (36.0) Site 3. 1670 (29.8) Site 4. 1764 (23.6) Site 5. 3773 (22.0)	Stand volume Pine straw Yield	Raking did not decrease growth, fertilization increased growth in loblolly Fertilization generally increased straw yield
[18] ANOVA, LSD, 1% alpha level	Florida Manderin, Hurricane Slash (Age 8–13)	NR, NF; R, NF; R2, NF; R3, NF; NR, F; R, F; R2, F; R3, F; R4, F; 40.8 kg N + 45.4 kg P	Not available	Diameter Height Disease incidence	R, NF 5 mm less than NR, NF Growth reduced with fertilization Pitch canker and fusiform rust increased significantly in the fertilized plots increasing mortality

[1] Treatments: no raking, no fertilization (NR, NF), rake Oi only, no fertilization (R, NF), no raking, fertilize (NR, F) (see study for fertilization details), R, F = rake Oi only, fertilize, R2 = rake Oi only on 2 year intervals, R3 = rake Oi only on 3 year intervals, R4 = rake Oi only on 4 year intervals.

Table 7. Summarization of statistical test results for loblolly and slash pine straw production and growth and yield variables by treatment, soil series, and study. Non-significant (NS), '*(-)' and '*(+)' indicates either a negative or positive response associated with significant variables (*), and '—' indicates that a statistical test was not reported for that variable and treatment combination.

				Treatment			
Species	**Study Reference**	**Soil Series**	**Variable**	**Raking**	**Fertilizer**	**Raking × Fertilization**	**Comments**
Loblolly	[24]	Fuquay	Straw Production	NS	NS	NS	Fertilization was numerically greater than the control
Loblolly	[24]	Fuquay	Annual basal area increment	NS	NS	NS	
Loblolly	[28]	Rigdon, Olustee, Dothan, Faceville	Straw Production	–	* (+)	–	Two of three sites were not significantly different
Slash	[28]	Tifton, Fuquay	Straw Production	–	* (+)	–	
Loblolly	[28]	Rigdon, Olustee, Dothan, Faceville	Annual basal area increment	NS	NS	NS	Mortality tended to be higher in fertilized than non-fertilized plots
Slash	[28]	Tifton, Fuquay	Annual basal area increment	NS	NS	NS	Mortality tended to be higher in fertilized than non-fertilized plots
Loblolly	[28]	Rigdon, Olustee, Dothan, Faceville	Annual volume increment	NS	NS	NS	Mortality tended to be higher in fertilized than non-fertilized plots
Slash	[28]	Tifton, Fuquay	Annual volume increment	NS	NS	NS	Mortality tended to be higher in fertilized than non-fertilized plots
Loblolly	[28]	Rigdon, Olustee, Dothan, Faceville	Mean annual dbh increment	NS	NS	NS	Increased with fertilization compared to rake only or control

A study addressing the effects of raking (no raking, annual raking, bi-annual raking, raking once every three years, and raking once every four years) and fertilization (two applications of 280.5 kg DAP ha^{-1} prior to and one year post-raking treatments in August 1991 and September 1992), or no fertilization was conducted in an old field slash pine stand between ages 8- and 13-years in Clay County, Florida [18]. Soils were Manderin and Hurricane series (sandy, siliceous, thermic Oxyaquic Alorthods and sandy, siliceous, thermic Oxyaquic Alorthods, respectively). Diameter, total height, and pine straw production rates were followed through age 13 years. During a single year, maximum pine straw production was 736 bales ha^{-1} for the annual rake, 934 bales ha^{-1} for the biennial rake, and 1094 bales ha^{-1} for the rake every four years treatment. Fertilization 101 kg N + 112 kg ha^{-1} elemental-P as DAP significantly (LSD at the 1% alpha level) increased N concentrations in the pine straw (p = 0.01). Soil available P was significantly higher in the rake every 4 years followed by the control treatment when compared to the annual rake treatment. Up to 50.4 kg ha^{-1} N and 5.0 kg ha^{-1} P were removed by raking pine straw annually. Raking every year significantly reduced diameter growth in all classes by an average of 5 mm over four years. Lopez-Zamora et al. [18] noted, similarly to McLeod et al. [22] and Haywood et al. [15], that the annual rake treatment had significantly fewer trees per hectare in larger dbh classes than the less frequent or no raking regimes four years after raking. This trend was no longer evident five years after raking. Fertilization and raking did not significantly affect basal area or total volume over the five-year study period on this highly fertile old field site. Pitch canker (*Fusarium moniliforme* var. *subglutinans*) and fusiform rust (*Cronartium quercuum* f. sp. *Fusiforme*) incidence increased significantly in the fertilized plots and was correlated to greater mortality in the fertilized vs. the unfertilized plots. The authors concluded that the most aggressive raking regime in this case (annual raking) may eventually deplete soil nutrition and reduce site productivity [18].

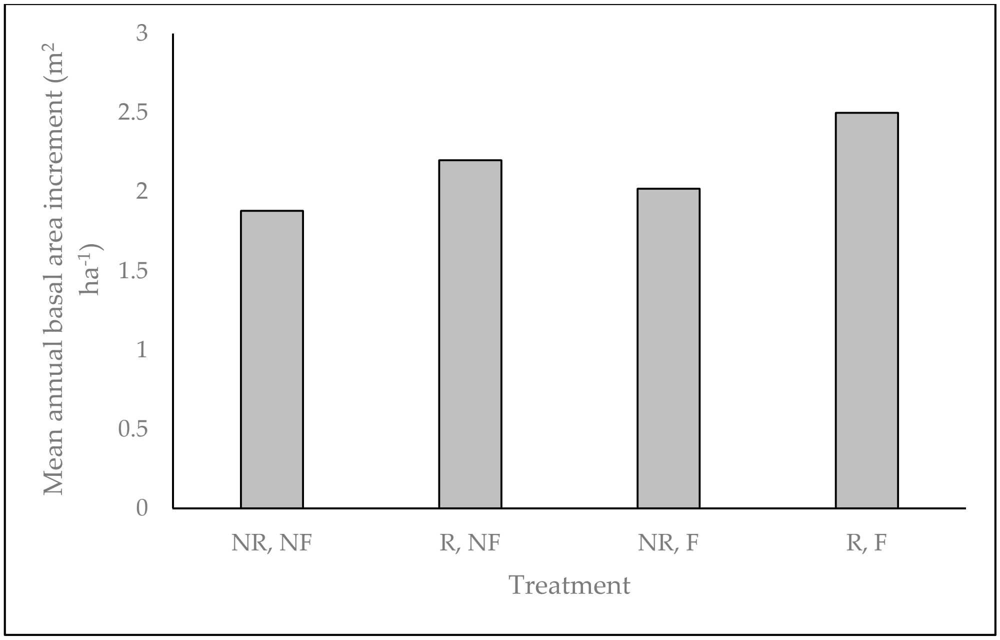

Figure 8. Mean annual basal area increment over the seven-year study period for loblolly pine by treatment [24]. Treatments: no rake, no fertilization (NR, NF); rake, no fertilization (R, NF); no rake, fertilization (NR, F); rake, fertilize (R, F) (refer to Tables 6 and 7 for study details, information on fertilizer treatments, and statistical test results).

A study by Ogeden and Morris [28] evaluated stand growth and straw yield in unthinned loblolly and slash pine stands on cutover and old field sites with well-drained soils in the Upper Coastal Plain of Georgia. Two of the stands were slash pine and three were loblolly pine. Four years of annual raking did not result in significant (Duncan's multiple range test at the 5% alpha level) decreases in stand basal area or volume growth for any of the five stands (Table 7). A single application of 224.4 kg N + 56.1 kg P + 56.1 kg K ha^{-1} at study initiation did not significantly increase pine straw production (Figure 9), basal area increment (Figures 10 and 11), or stem volume growth (Figures 12 and 13). Increased mortality reduced volume growth with fertilization on the old field slash pine site. Pine straw yields generally increased with increasing basal area. Although NPK fertilization produced more pine straw, increased understory vegetation decreased pine straw harvest yields. Annual pine straw removal did not significantly reduce pine volume growth during the five-year study period. While statistically non-significant, fertilization increased growth in the cut-over loblolly pine stands whether or not the stands were raked yet not on old field sites (Figure 14). Slash pine stands were less responsive to fertilization, and mortality was significantly greater for the fertilizer treatment at the Albany site (Figures 11 and 13) [28].

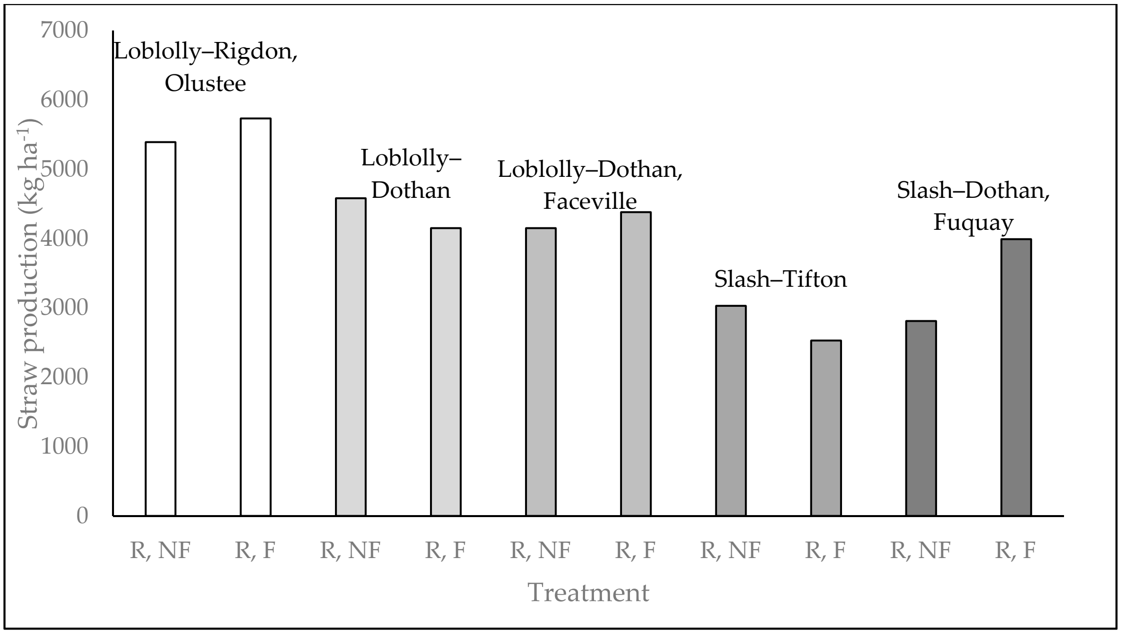

Figure 9. Loblolly and slash pine straw production three years after treatment [25]. Treatments: no rake, no fertilization (NR, NF); rake, no fertilization (R, NF); no rake, fertilization (NR, F); rake, fertilize (R, F) (refer to Tables 6 and 7 for study details, information on fertilizer treatments, and statistical test results).

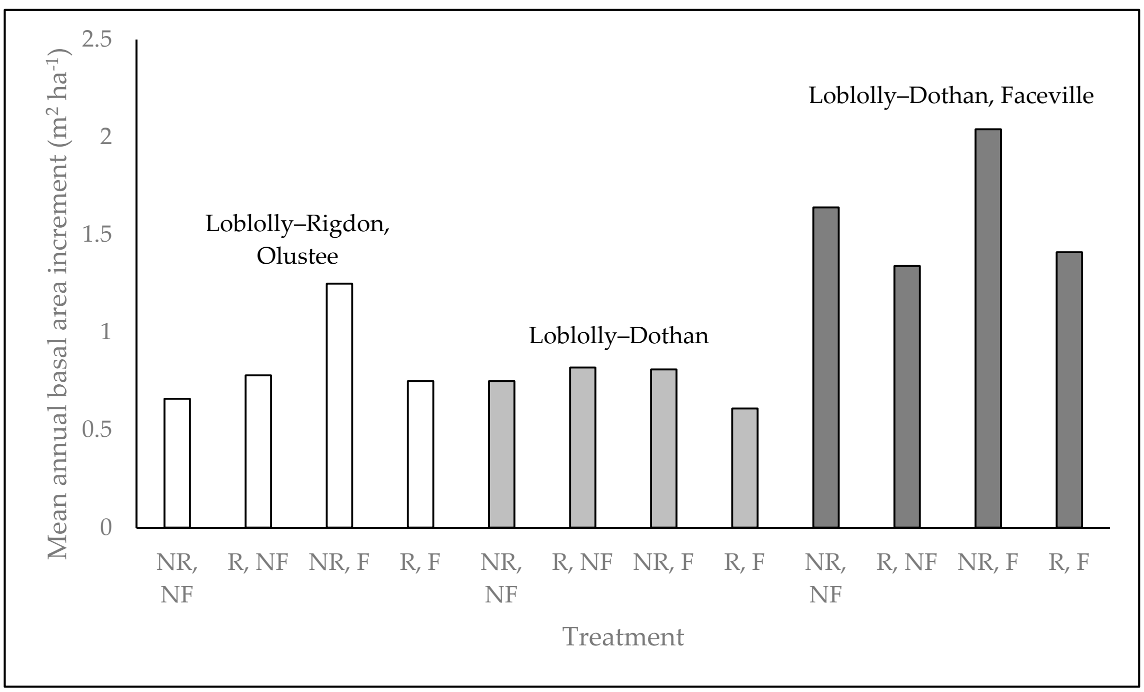

Figure 10. Mean annual basal area increment over the five-year study period for three loblolly pine sites by treatment [25]. Treatments: no rake, no fertilization (NR, NF); rake, no fertilization (R, NF); no rake, fertilization (NR, F); rake, fertilize (R, F) (refer to Tables 6 and 7 for study details, information on fertilizer treatments, and statistical test results).

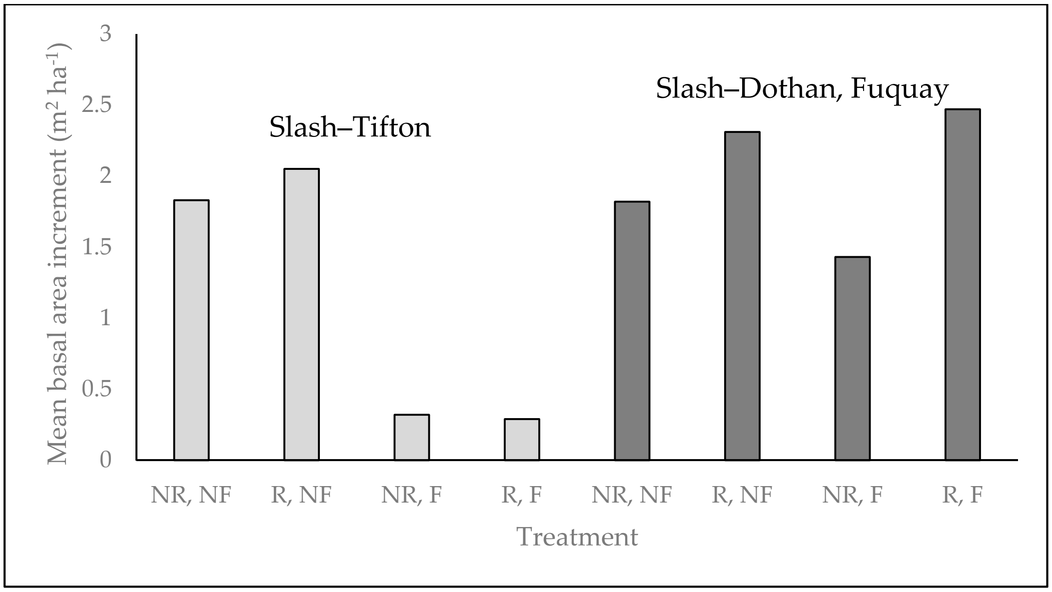

Figure 11. Mean basal area increment over the five-year study period for two slash pine sites by treatment [25]. Treatments: no rake, no fertilization (NR, NF); rake, no fertilization (R, NF); no rake, fertilization (NR, F); rake, fertilize (R, F) (refer to Tables 6 and 7 for study details, information on fertilizer treatments, and statistical test results).

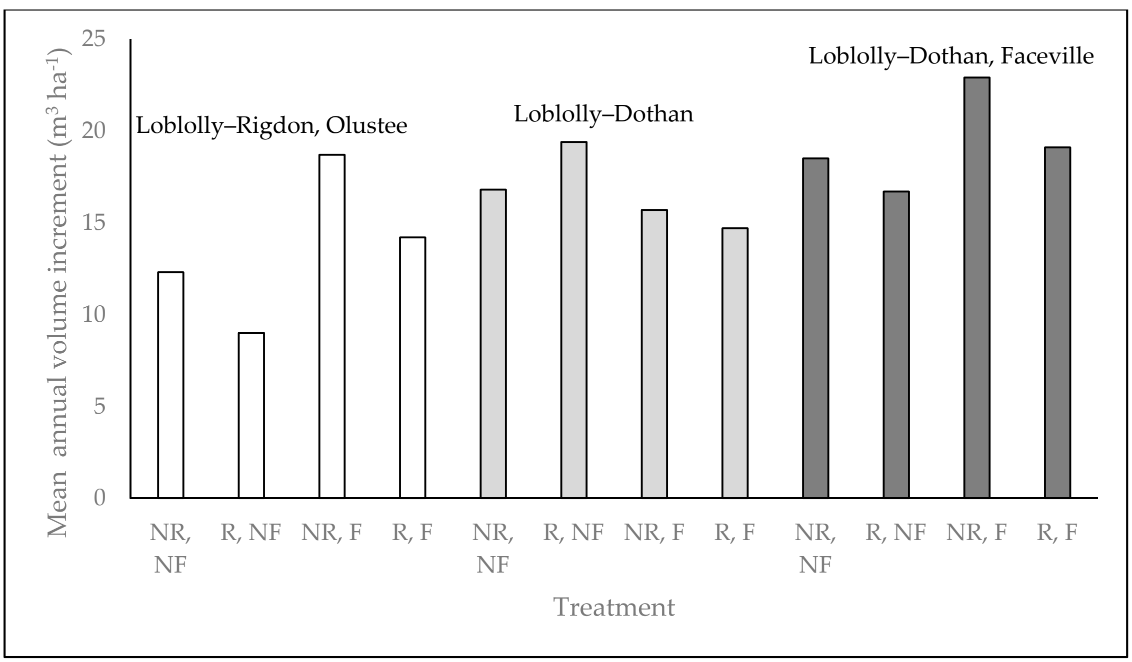

Figure 12. Mean annual volume ha growth over the five-year study period for three loblolly pine sites by treatment [25]. Treatments: no rake, no fertilization (NR, NF); rake, no fertilization (R, NF); no rake, fertilization (NR, F); rake, fertilize (R, F) (refer to Tables 6 and 7 for study details, information on fertilizer treatments, and statistical test results).

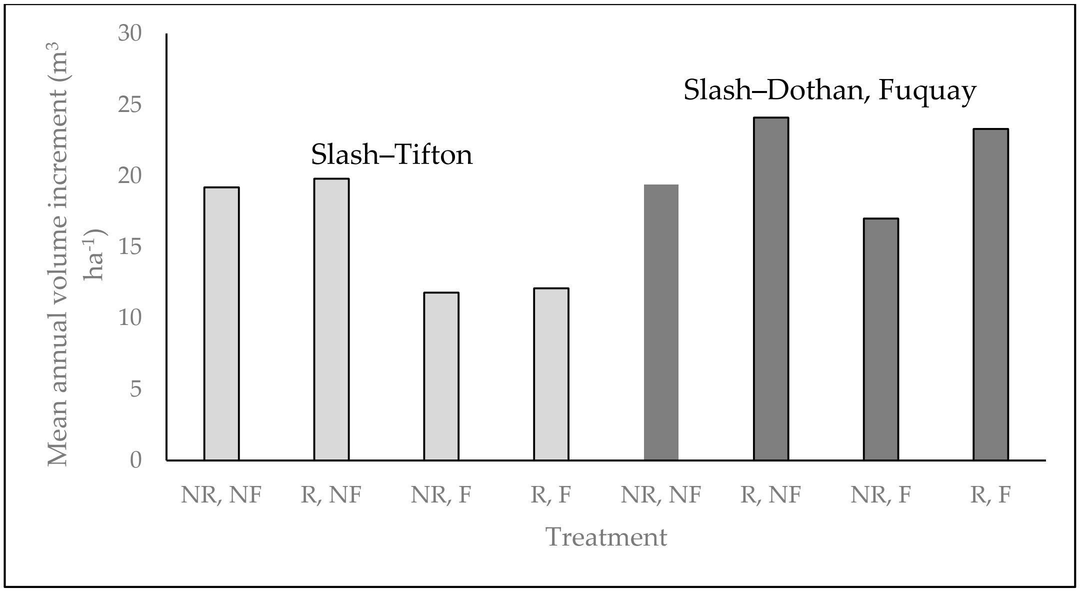

Figure 13. Mean annual volume increment over the five-year study period for slash pine by treatment [25]. Treatments: no rake, no fertilization (NR, NF); rake, no fertilization (R, NF); no rake, fertilization (NR, F); rake, fertilize (R, F) (refer to Tables 6 and 7 for study details, information on fertilizer treatments, and statistical test results).

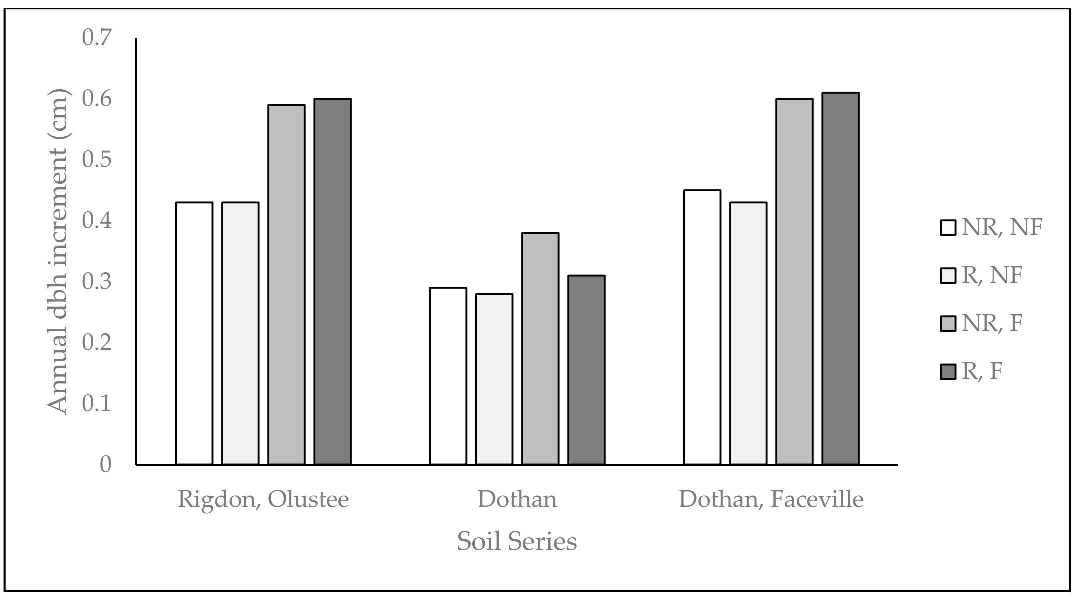

Figure 14. Loblolly pine mean annual dbh increment over the five-year study period by site [25]. Treatments: no rake, no fertilization (NR, NF); rake, no fertilization (R, NF); no rake, fertilization (NR, F); rake, fertilize (R, F) (refer to Tables 6 and 7 for study details, information on fertilizer treatments, and statistical test results).

2.3. Summary

1. Pine straw yields from annual raking regimes without fertilization were reduced compared to pine straw yields from no raking sites [18,22,24] in the majority of studies (non-old field sites).

2. Conversely, fertilization (either raked, fertilized or no rake, fertilized) on marginal soils or on cut-over sites maintained [15,25] or increased pine straw production [19,23,27] over raked, unfertilized, or unraked, unfertilized stands, respectively.
3. Annual pine straw yields from the aforementioned studies ranged from 2243 to 4263 kg ha^{-1}) [19,22,24] for longleaf pine. Loblolly pine straw yield ranged from 2243 to 5609 kg ha^{-1} [23,25] Slash pine straw yields ranged from 2243 to 4262 kg ha^{-1} [25], while results from [17] reported maximum yields of 5048.3 kg ha^{-1} on cut-over sites. Pine straw yields increased to 8974 kg ha^{-1} on fertile old field sites [18]. The upper end pine straw yields of 5048 to 5609 kg ha^{-1} for slash and loblolly pine on cut-over sites were also suggested by [3,20,29]. Morris et al. [17] noted that for young, fully stocked slash pine plantations for every 2.3 m^2 ha^{-1} of cumulative basal area, pine straw production increases by approximately 561 kg ha^{-1}.
4. Three studies reported that annual raking without fertilization reduced dbh increment significantly one [22] (Troup soil), two [22] (Fuquay soil), three [15], or four [18] years after raking commenced.
5. Raking on a three-year interval without fertilization did not significantly affect pine growth over a four [18] or seven-year period [24].
6. Raking and fertilization did not significantly improve longleaf pine growth post-thinning, improvements in pine straw production were variable [27,28].
7. Young pine stands planted on old field sites with a high residual fertilizer level (above sufficiency soil P) appear to have no significant fertilization benefit for increasing pine straw production or wood volume [18,25].
8. Tree mortality and disease incidence can increase significantly with fertilization and annual intensive pine straw raking [18,25] in unthinned stands with a high basal area.
9. Understory vegetation was noted to greatly increase with NP or NPK fertilization, reducing the rakeable portion of the stand and increasing the need for competition control herbicides [15,25].

3. Discussion

3.1. Fertilization Trends

Our review suggests there are probably differences in the sensitivity of longleaf vs. loblolly and slash pine to pine straw raking and fertilization. This is the result of both differences in site characteristics on which we tend to find these species (longleaf on infertile, droughty soils and loblolly and slash on more fertile, wetter soils) as well as the inherent ability of each species to respond to improved nutrition [30–32].

The forest floor has a major impact on forest stand growth through its role as a major nutrient pool and regulator of nutrient release, surface mulch that moderates infiltration, surface evaporation, soil moisture, temperature, and as habitat for soil organisms. Pine straw raking can affect many of these roles. From the standpoint of tree growth response, the major near-term effect of raking pine straw may be the result of increased moisture stress; however, some evidence existed for reduced nutrient availability where straw was raked in the absence of fertilization.

Pine growth, in particular diameter growth [15,18,22], and pine straw production decreased in almost all studies in the near-term (one to four years after annual raking was initiated) where raking annually without fertilization was imposed. However, raking just the litter layer every three to four years appears to have little adverse impact on tree growth [18,24]. Without fertilization, sites with more marginal soil fertility and moisture status (deep, excessively drained sandy soils such as Lakeland, Kershaw, Alpin, Foxworth; Typic or Lamellic Quartzipsamments and Troup, Blanton; Grossarenic Udults) have a greater chance of negative impacts to tree growth with successive annual raking operations.

Fertilization was shown to increase pine straw production in the majority of cases cited here. Notable exceptions were loblolly and slash pine on fertile old field sites [18,28] (Figure 8) as well as most years (3 of 4) straw was raked in the post-thinning longleaf pine study which was on a moderate to good productivity site [26].

Fertilization increased basal area or wood volume production where pine straw was raked when compared to unfertilized, raked plots in the Ross et al. [24] loblolly study, the Haywood et al. [15] longleaf study, and the Ogden and Morris [28] cut-over loblolly studies. This trend did not occur in the two post-thinning longleaf studies [26,27]. In three cases where fertilization did not increase wood production, plot mortality problems existed (Ross et al. 1995 longleaf study) or on old field sites that had high residual fertility [18,28]. The studies with increased mortality due to fertilization occurred in unthinned slash pine stands [18,28] or in stands with high basal areas [24]. Ogden and Morris [28] found that three cut-over, unthinned loblolly and slash pine sites responded to fertilization regardless of whether pine straw was raked or not, whereas the two fertile, old field site loblolly and slash stands did not respond positively to fertilization.

Nutrient return to the organic soil horizons in litterfall is considered an important component of the nutrient cycle and is often cited as a major reason pine stands flourish on relatively nutrient poor sites [33]. Nutrient balance studies show that through a rotation or more, this must be true. However, results from these studies are consistent with recent studies that show relatively slow release of N [3] from an organic-N form to a plant available form (NH_4-N or NO_3-N) and other nutrients from O horizons of southern pine stands [34,35]. It seems that even sites that respond to fertilization with N, P, and K are insensitive to removal of equivalent or greater amounts in pine straw harvest. The longest reported study of pine straw raking in southern pine stands to date is seven years, so direct evidence for long-term productivity declines in the absence of fertilization do not exist. Nevertheless, a proactive approach to fertilization seems reasonable and a fertilization program should be included in stands from which pine straw will be annually harvested for greater than a four to five consecutive year period.

3.2. Fertilization Recommendations for Enhancing Pine Straw Production in Loblolly, Longleaf, and Slash Stands

The aforementioned cited results indicate that fertilization can balance nutrient budgets, maintain or increase straw yields, and maintain or increase wood volume growth in pine stands intensively managed for straw production through a period of three to seven years. Recommended rates, frequency of application, and fertilizer forms differ based on species, stand conditions and site factors. Tables 8 and 9 detail the recommended fertilization rates and forms for loblolly, longleaf, and slash pine stands to be raked semi-annually or annually.

These recommended nutrient application levels are based on southeastern U.S. land grant university forest research cooperative findings [36]. These recommended application levels could be modified to specific site, species, and stand characteristics, and landowner objectives. To date, fertilization of old field planted loblolly and slash pine sites with a relatively high residual fertility do not appear to respond to NP [18] or NPK [25] fertilization. When multiple stands are being raked, then stands should be ranked based on probability of response to fertilization.

Generally, we recommend fertilization at 5-year intervals for these stands if stands are planned for annual raking for eight to ten years or longer (Table 8). If stands are planned for raking for less than eight years, then a single application of the aforementioned nitrogen, phosphorus and potassium when needed can be used. If a single application or a 5-year fertilizer schedule is employed for loblolly and slash pine, N application rates should range from 168.3 to 224.4 kg ha^{-1} and P between 28 to 56.1 kg ha^{-1} [36,37]. Potassium (K) fertilization at rates between 56.1 and 89.7 kg ha^{-1} is also recommended in stands after canopy closure [38] where foliar K is less than 0.30% (slash and longleaf) or 0.35% (loblolly). Potassium additions

(50 56.1 kg K ha^{-1}) to standard NP fertilization in thinned slash pine stands significantly increased dbh and height growth nine years after treatment in Louisiana [38]. In young longleaf pine, N application should be about 84.1 kg ha^{-1} increasing to between 112.2 to 140.2 kg ha^{-1} for stands with mean dbh greater than 15.2 cm [19].

Table 8. Recommended fertilizer rates for a five-year application regime.

Species	Age (Years)/ Size (dbh cm)	N (kg ha^{-1})	Elemental-P (kg ha^{-1})	Elemental-K [3] (kg ha^{-1})	Other Nutrients [4] (kg ha^{-1})
Loblolly [1]	8 to 30^{+} y	168–224	28 (Piedmont Region) 28 or 56 (Coastal Plain Region)	56–89	as needed based on foliar analysis
Longleaf	<15 cm dbh	84	28 or 56 (Coastal Plain Region)	56–89	as above
Longleaf	≥15 cm dbh	84–168	as above	56–89	as above
Slash [2]	8 to 30^{+} y	168–224	28 or 56 (Coastal Plain Region)	56–89	as above

[1,2] Use lower N level just before or at canopy closure and higher N level at or after thinning. When in an unthinned stand, N should be applied in split applications over 2 to 3 years where fusiform rust canker incidence is greater than 30% in loblolly pine stands and greater than 25% in slash pine stands. [3] As needed based on foliar analysis. If less than 0.35% for loblolly, 0.30% for longleaf, and 0.25 to 0.30% for slash then K is recommended (112 kg 0-0-60 ha^{-1} = 56 kg elemental-K ha^{-1} and 179.3 kg 0-0-60 ha^{-1} = 89.7 kg K ha^{-1}). [4] As needed based on foliar analysis. If Ca is less than 0.12% for loblolly, 0.10% for longleaf, and 0.08 to 0.12% for slash pine then 22.4–28.0 kg Ca ha^{-1} is recommended. If Mg is less than 0.07% for loblolly, 0.06% for longleaf, and 0.04 to 0.06% for slash pine then add 28 kg Mg ha^{-1} as K-mag or some other Mg form. If S is less than 0.12% for loblolly pine and 0.10% for longleaf or slash pine, then add 22.4 to 33.6 kg S ac^{-1}. If foliar B is less than 4–8 ppm then add 0.5 kg B ha^{-1}, and if Cu is < 2–4 ppm then add 1.4 kg ha^{-1}.

Table 9. Fertilizer application rates for loblolly, longleaf and slash pine at or after canopy closure using common fertilizer forms based on Table 2 N and P recommendations.

Species	Rate (kg ha^{-1}) of N + Elemental-P	N as Urea + P as DAP (kg ha^{-1})	K as Muriate of Potash (MOP: 0-0-60) (kg ha^{-1})
Loblolly Pine [1] and Slash Pine [2]	168.1 N + 28.0 P	308.2 urea + 140.0 DAP	112 to 170 MOP
	168.1 N + 56.0 P	255.5 urea + 280.2 DAP	112–170 MOP
	224.2 N + 28.0 P	432.6 urea + 140.1 DAP	112–170 MOP
	224.2 N + 56.0 P	377.7 urea + 280.2 DAP	112–170 MOP
Longleaf pine	84.0 N + 28.0 P	127.8 urea + 140.1 DAP	112–170 MOP
mean dbh < 15 cm	84.0 N + 56.0 P	72.9 urea + 280.2 DAP	112–170 MOP
Longleaf pine	140.1 N + 28.0 P	249.9 urea + 140.1 DAP	112–170 MOP
mean dbh ≥ 15 cm	140.1 N + 56.0 P	195.0 urea + 280.2 DAP	112–170 MOP

[1,2] Use lower N level just before or at canopy closure and higher N level at or after thinning. When in an unthinned stand, N should be applied in split applications over 2 to 3 years where fusiform rust canker incidence is greater than 30% in loblolly pine stands and greater than 25% in slash pine stands. Hardwood basal area ha^{-1} should be less than 10% of stand basal area ha^{-1} for all three species when pine straw and pine wood volume gains are high priority.

Two- to five- year fertilization intervals are possible where raking and fertilization logistics can be worked out. Peak current annual volume increment response for loblolly pine occurs two to four years after NP fertilizer application [36]. Jokela and Stearns-Smith [39] concluded that split fertilizer N applications (50 N + 50 P ac^{-1} (56.1 + 56.1 kg ha^{-1}) at study initiation and 150 N ac^{-1} (168.3 ha^{-1}) two years later in mid-rotation slash and loblolly pine stands gave similar growth responses as a single NP fertilizer dose (224.4 N + 56.1 P ha^{-1}). This split application of N may be financially attractive as over one-half of the fertilizer cost is deferred for two years [39].

Urea ((CO(NH_2)$_2$), 46-0-0) is the most common form of N fertilizer used for forest fertilization because of its high N analysis, although some slow release N fertilizer materials are showing great promise recently in forest fertilization due to low N losses via volatilization [40,41]. It is usually applied in the cool winter months to minimize N-volatilization losses. Ammonium nitrate (NH_4NO_3, 33-0-0) is also a suitable source of N and it does not have the volatilization loss potential of urea. However, N can be lost as nitrate and these losses can be substantial on coarse textured soils. Diammonium phosphate (DAP ($(NH_4)_2HPO_4$), 18-46-0) is the preferred P source due both to its high solubility and because it supplies a portion of the N fertilizer requirement. The most common potassium (K) fertilizer form is muriate of potash (0-0-60). Typically, where K is needed, 112 to 170 kg of 0-0-60 is added to N plus P fertilizer prescriptions to obtain 56 to 85 kg ha^{-1} of elemental K. It is uncommon for pine stands to have calcium (Ca), magnesium (Mg), sulfur (S), manganese (Mn), boron (B), or copper (Cu) deficiencies. Jokela et al. [42] found that the addition of 89.7 kg Mn ha^{-1} applied in a 7-year-old slash pine stand on a poorly drained Ultic Haplaquod increased wood volume by 2.01 t ha^{-1} y^{-1} during the next five years on sites where foliar Mn was 20–80 ppm or less. Foliar analysis for these nutrients can determine whether there is a need for the addition of these nutrients.

The use of diagnostic tools such as: leaf area index (LAI) done in mid-summer at LAI peak, soil sampling (for soil test P, based on procedure if <4–6 ppm or 9.0 to 13.5 kg ha^{-1} then P is deficient), foliar sampling (done in winter months, 10–20 dominant trees/stand, upper 1/3 crown, south-facing side, first flush of previous year's growth), and knowledge of soils can be beneficial for prescribing fertilizer applications. These diagnostic tools are valuable when several stands are to be raked and fertilized and ranking or prioritizing stands would be cost-beneficial. Knowledge of foliar nutrient status, soil available P, soil series, and LAI prior to stand fertilization can serve as a baseline for (1) comparing changes (magnitude) in foliar nutrient status, soil P levels, and LAI after fertilization, and (2) when re-fertilization should occur (duration) and with what nutrients. Post-fertilization LAI, foliar, and soil sampling should be done prior to the next planned fertilizer application (two to five years after first application) to tailor the prescription to stand needs. Commonly, stands are fertilized initially with N+P. Subsequent fertilizer applications may entail the addition of K, Ca, S, Mg, or micro-nutrients as these nutrients become depleted. Foliar analysis can indicate stand needs of N, P, K, Ca, Mg, S, Mn, B, and Cu.

It is recommended, where possible, to retain the two lower layers (fermentation (Oe) and humus (Oa) layers) of slightly to advanced decayed needles and other organic material to reduce evaporative losses. Fertilizer applications should be timed to minimize nutrient losses to raking displacement, leaching, denitrification, or volatilization. The raking timing may have to be modified (commonly done in late fall to mid-spring) to accommodate winter urea application. Erosion potential should be considered. Raking is not recommended where slope is greater than 8%. The raking frequency should be based on inherent soil water holding capacity, cation exchange capacity, percent organic matter, and fertility site factors. Droughty, infertile soils with low CEC and organic matter may be scheduled for raking only the litter layer on three- to four- year cycles to maintain acceptable tree growth rates. Fertilization can aid in enhancing tree growth and pine straw production on these marginal soils [19,26] when raking occurs in three- to four-year cycles.

Good competition control is essential to keep raked stands clean, particularly after fertilization. Good competition control can also have stand growth benefits. Studies by Fortson et al. [43] and Oppenheimer et al. [44] noted that complete weed control in age 9- to 15-year-old slash and loblolly pine stands increased wood volume production by 2.01 and 3.03 t ha^{-1} y^{-1} for 8 to 14 years in unraked stands, respectively. Hardwoods should be controlled when the hardwood basal area is greater than 10 percent of stand basal area.

Nitrogen fertilization in stands with a high incidence of stem fusiform cankers in loblolly and slash pine stands (>25% for slash and >30% for loblolly) should be applied in split applications over two to three years to minimize stem breakage. Lopez-Zamora et al. [18] found that pitch canker and fusiform rust incidence increased in old field slash pine fertilized plots which increased mortality. Overloading stands with high rates of fusiform rust with a large single dose 168.3 to 224.4 kg ha^{-1} of N greatly increases crown volume and weight and some stems cannot handle the sudden weight gain. Special care should be taken in a longleaf and slash pine stands that are on the northern edge of their native range where periodic ice or snowstorms can weigh down crowns and cause excessive stem breakage. Lower N doses or split application of N may reduce possible stand damage from ice or snowstorms. Overloading younger longleaf stands (mean dbh <15.2 cm) with too much N in a single dose (>112.2 kg ha^{-1}) can cause unacceptable mortality [19].

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