SOIL CARBON AND SOIL PHYSICAL PROPERTIES RESPONSE TO INCORPORATING MULCHED FOREST SLASH*

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ABSTRACT

A study was installed in the Lower Coastal Plain near Washington, North Carolina, to test the hypothesis that incorporating organic matter in the form of comminuted forest slash would increase soil carbon and nutrient pools and alter soil physical properties to favour pine growth. Two sites were selected, an organic and a mineral site, to compare the treatment effects on the different soil types. The mulching treatments included a surface broadcast mulch, a surface strip mulch, and a strip mulch and till. On the mineral site, the three treatments resulted in general decreases in soil bulk density, gravimetric soil water content, and soil strength. Soil carbon and nitrogen increased for all the treatments on the mineral site, with some significant differences between the treatments. The broadcast mulch and bed treatment resulted in an almost 100% increase in soil carbon and nitrogen. On the organic site, the treatments did not have a significant effect on soil physical properties or soil carbon and nitrogen. There was a consistent decrease in soil carbon and nitrogen on this site but these changes were not significantly different from those in the control treatment.

Keywords: mulch; till; soil carbon; bulk density; soil strength.

INTRODUCTION

The geochemistry and climate of the southern United States are such that forests are dependent on soil organic matter (SOM) dynamics for adequate nutrition. Soil organic matter is the major source of plant-available nitrogen and provides as much as 65% of the total soil phosphorus (Bauer & Black 1994). Soil parameters, including total soil carbon, account for many site quality indicators being collected. However, nutrient turnover rates are generally more relevant to forest productivity than is total soil carbon (Cole & Rapp 1981; Edmonds & Hsiang 1987; Binkley & Hart 1989). Total SOM on a site is, at best, a key to long-

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term productivity potential or carrying capacity. What may be more important to short-term (i.e., annual) productivity is the dynamic relationship between the labile fraction of the SOM pool and plant growth. It is this labile fraction that is most sensitive to environmental change and variations in this fraction will have the most immediate impact on forest ecosystem productivity (Ruark & Blake 1991; Wander *et al.* 1994; Eswaran *et al.* 1995).

Accurate knowledge of carbon dynamics at the landscape and regional scales is needed to predict and manage forests. Presently, models that evaluate the potential effects of climate change on forest sustainability include a limited amount of information on carbon dynamics. Improving our understanding of carbon processes relative to common soil variables, such as texture, will contribute to the accuracy of models that predict the role of climate change on forest dynamics. Besides regulating forest productivity, SOM dynamics are critical to carbon sequestration. The environmental constraints on sequestering carbon in a given soil system are not well understood. Evidence exists suggesting that there may be a negative feedback between SOM levels and carbon allocation to plant root systems that limits carbon storage in the soil (Ruark & Blake 1991). Significant increases in the recalcitrant SOM fractions may suggest the potential for carbon sequestration. Since this fraction has been linked to the soil's physical properties (Elliot 1986; Beare *et al.* 1994), fluxes in the size or chemical identity of this fraction may result in significant long-term changes in the soil.

Careful management of forest soils is essential for achieving optimal sustainable productivity of forest ecosystems. Management systems comprising appropriate harvest, regeneration, and silvicultural options can be used to reach this goal. Extensive evidence exists that extreme soil disturbance results in a loss of SOM, which subsequently contributes to the elevated atmospheric carbon dioxide concentration (Schlesinger 1995). Stabilising the SOM in forests can aid in reaching optimal sustainable productivity without exacerbating the elevated atmospheric carbon dioxide problem. While oxidation of SOM contributes to atmospheric carbon dioxide, increasing the recalcitrant SOM pool could reduce feedback to atmospheric carbon dioxide levels (Schlesinger 1995).

Significant areas of forest soils in the south exist in degraded condition due to past land use practices, primarily agricultural, or are inherently carbon and nutrient poor. Many of these sites have been converted to pine plantations. At maturity, these plantations are commonly clearcut, bedded, and replanted with pines. Clearcutting is the most economical and efficient method of harvesting these stands, but the harvesting and subsequent site preparation may have negative impacts on the soil and SOM. For example, compaction may alter soil structure and reduce gas exchange and water movement, and the removal of organic matter can exacerbate nutrient deficiencies on already degraded soils. Restoring degraded soil and enhancing inherently poor soil can lead to increased productivity and carbon sequestration in forest systems. Addition and incorporation of organic matter has significant potential for restoring and enhancing soil systems, increasing sustainable levels of productivity, and increasing both short- and long-term carbon sequestration by forest systems (Buford *et al.* 1999). An effective means of increasing and stabilising soil organic matter is through the application of organic soil amendments, and forest biomass in the form of logging residues is usually a readily available source. Surface application of mulched plant material can provide protection from erosion, conserve moisture, and moderate soil temperature. However, little of the mulched material is initially incorporated into the soil and the potential for soil compaction exists. Incorporating the mulched material by tilling the soil can enhance soil structure and loosen the soil, permitting improved air and water infiltration. However, the soil will be exposed and oxidation of SOM will be more rapid than on sites where the mulch is on the surface. Another consideration is that many mulched plant materials have a high C:N ratio and will tie up large amounts of nitrogen during decomposition, thus reducing nutrient availability for the new vegetation. Including fertiliser application in the site preparation may provide enough nutrients to replace those tied up in the mulch.

This paper describes the changes, over 1 year, in soil carbon and the soil status at treatment installations on two stands on which logging residue was mulched and incorporated into the soil. Comparisons with conventional and control treatments are also discussed. Additionally, a cost assessment for each of the treatments on each stand is presented.

MATERIALS AND METHODS

Site Description

The study was installed in October 1997 to compare mulching and tilling with conventional site preparation techniques on two sites: a wet pine flat with a sandy loam horizon over a clay horizon (mineral site), and a pocosin site with deep organic soil (organic site). The study sites were located in the Lower Coastal Plain region of eastern North Carolina in Beaufort County. This area of the Coastal Plain is characterised by flat topography with an average elevation of 25 m and dissected by numerous streams and rivers. The area receives approximately 1346 mm of precipitation per annum, with 55% of the total received between April and September of each year. Average temperatures range between 2° and 30°C, with an average winter temperature of 8°C and an average summer temperature of 25°C. Soil development within this region has occurred in clayey and/or loamy marine and fluvial sediments and includes members of the Ultisol, Histosol, Spodosol, and Entisol soil orders (USDA Natural Resources Conservation Service 1995). A majority of the county is represented by soils of the Ultisol order. The study sites under evaluation have been mapped as Leaf-Lenoir-Craven in the mineral soil site and Bayboro-Leaf-Craven soils in the organic site. The former are characterised by loamy surface textures with a predominantly clay subsoil that can be moderately well to poorly drained and are found on broad flats and upland ridges, and in shallow depressions. The latter are characterised by loamy and mucky soil surface layers underlain by loamy to clayey subsoil that are poorly and very poorly drained soils found on broad flats and in depressions. The stands were loblolly pine (*Pinus taeda* L.) plantations that had been clearcut and were to be replanted with the same species. These sites were selected to isolate the effect of adding additional woody organics to the soil. Mulching the slash and stumps as a treatment was compared to mulching and tilling into the soil as another treatment. Finally, a comparison was made between mulching strips and broadcast mulching.

A Rayco* Model T275 Hydra-Stumper was used to install the study. The machine had a 2.4-m horizontal rotating drum with 36 attached swing hammers that: (1) mulched logging slash, stumps, and humus layer, (2) tilled the soil approximately 20 cm deep, and (3) mixed woody biomass into the soil. The machine was track mounted and powered by a 205-kw engine. The conventional operation included one pass of a dozer with a KG V-blade to shear

* The use of brands and trade names is for the convenience of the readers and does not imply an endorsement by the USDA Forest Service, Weyerhaeuser Company, or Virginia Tech.

stumps and roll logging debris to the sides to clear the strip for bedding. Another dozer was used on the second pass to apply fertiliser and to bed with a disk bedding plough.

Treatments

The treatments differed by soil type. On the organic site, the treatments were:

- Control (CON): no mulching, no V-shearing, no bedding, no fertiliser, no weed control
- Conventional (CVN): V-shearing, bedding, fertiliser, weed control
- Strip mulch (SM): bedding, fertiliser, weed control
- Strip mulch/till (SMT): tilling, bedding, fertiliser, weed control

On the mineral site, the treatments were:

- Control (CON): no mulching, no V-shearing, no bedding, no fertiliser, no weed control
- Conventional (CVN): V-shearing, bedding, fertiliser, weed control
- Strip mulch (SM): bedding, fertiliser, weed control
- Strip mulch/till (SMT): tilling, bedding, fertiliser, weed control
- Broadcast mulch (BAB): bedding, fertiliser, weed control
- Broadcast mulch (BNB): no bedding, fertiliser, weed control

The plots were 40 × 40 m (0.16 ha) with a measurement area of 20 × 20 m (0.04 ha). The area was divided into blocks based on logging traffic and micro-elevation, and had four blocks per treatment in close proximity to ensure uniformity of residual slash, stump size and distribution, and soil.

Methods

A productivity assessment was performed on the Rayco T275 Hydra-Stumper. Three productive elements were evaluated for the machine on each plot: travel, cut, and turn. Travel was defined as beginning with forward motion of the tyres and ended when forward motion of the tyres ceased. The cut element began when forward motion of the tyres ceased and ended when cutting/grinding of stumps/logs was complete and forward motion of the tyres resumed. The turn element began when the machine head crossed the plot boundary and began processing material on the ground with tyres in forward motion, thus beginning another pass. Productive and non-productive delays were also recorded. A CAT D7G crawler tractor was also monitored while performing the shearing and bedding. The crawler was equipped with a 3.7-m V-shear and a Savannah bedding plough.

Three treatments were evaluated for the Rayco; these included broadcast mulch, strip mulch/soil till, and strip surface mulch. A conventional treatment was also applied for comparison purposes. All four treatments were applied on the mineral site. On the organic site, only the strip surface mulch, strip mulch/soil till, and conventional treatments were applied. Treatments were replicated four times on each site and are defined as follows.

Broadcast mulch: The processing head was placed at ground level so that material on the surface was mulched and distributed over the entire area. Half of the broadcast mulch plots were later flat planted while the other half were bedded and planted.

Strip mulch/soil till: The treated area consisted of 3.7-m-wide strips on 5.5-m centres across the plot. However, instead of the processing head operating on the surface of the ground, it was lowered into the ground approximately 20 cm to create a tilling effect.

Strip surface mulch: The treated area consisted of 3.7-m-wide strips on 5.5-m centres across the plot. As with the broadcast treatment, the processing head was placed at ground level so that material on the surface was mulched and distributed over the treated area. All of the strip surface mulch plots were later bedded and planted.

Conventional: Consisted of shearing and bedding.

The amount of downed woody material present on each treatment plot was measured (Brown 1974). Downed woody material was divided into four size classes for recording: 0–0.6 cm, 0.6–2.5 cm, 2.5–7.6 cm, and >7.6 cm. All material 0–2.5 cm in size that crossed the sampling plane was recorded only between 0 and 1.8 m. Material 2.5–7.6 cm in size was recorded only to 3.7 m. Material >7.6 cm in size was recorded along the total length of the transect (10.7 m). Each piece >7.6 cm was measured to the nearest 0.25 cm using callipers. In addition, each piece was classified as being either solid or rotten.

Fuel wood depth was measured to the nearest 1.3 cm at 0, 0.3, and 0.6 m along each transect. Depth was defined as the vertical distance from the bottom of the litter layer to the highest intersected dead particle (Brown 1974). Vertical duff depth was measured to the nearest 0.25 cm using a ruler at 0.3 and 0.6 m from the transect origin.

To assess stump density, two 0.02-ha fixed-radius plots were installed within each plot on the mineral site. Since stump density was much lighter on the organic site, 0.04-ha fixed-radius plots were used. Stump diameters within each fixed-radius plot were measured to the nearest 0.25 cm. Stump heights were measured to the nearest 1.3 cm.

The relationship between tillage treatments and soil response was assessed through the measurement of soil strength, bulk density, and gravimetric water content within the measurement plots of each treatment area. Soil cores for the measurement of soil bulk density and gravimetric water content were collected by a soil core apparatus with an interior diameter of 6.7 cm outfitted with a plastic liner, to a depth of 0.5 m in three locations in each measurement plot. Soil cores were removed from three locations—the middle of each measurement plot and two equally spaced locations along a diagonal within the measurement plot area. Soil cores were subdivided into 0.10-m increments, weighed in their field moist state, and oven dried to obtain dry soil weights (Blake & Hartge 1986). The final volume of soil utilised to estimate bulk density was approximately 246.35 cm^3 based on dimensions of a core diameter of 2.9 cm and a height of 10.16 cm. Final soil dry bulk density and gravimetric water contents were computed using standard equations, with dry soil and water content weights as input variables. Soil strength data were collected with a Rimik CP20 recording cone penetrometer in 0.025-m increments to a depth of 0.5 m (American Society of Agricultural Engineers 1997). Penetrometer measurements were taken in nine locations within each measurement plot: plot centres, measurement plot corners, and halfway between the plot centres and corners on two diagonals. Altogether, 900 and 720 insertions were performed in the mineral and organic sites, respectively, for each in-bed, off-bed, and flat-planted location. Mean cone index values reported in this study represent the average of all insertions per treatment within a depth range of 0.10 m. Soil samples and penetrometer measurements were conducted in all treatments but two locations in bedded treatments were evaluated: in-bed and off-bed locations. Only the initial results for in-bed measurements are reported in this paper. A future publication is planned encompassing all components of the study upon completion of all study measurements.

Prior to treatment installation, soil samples were collected from the upper 15 cm of the soil with a 2.0-cm-diameter soil corer from 20 random locations within each site. After treatment installation, additional soil samples were collected from five locations within each measurement area of each treatment plot. These five points included the four corner points and a central point of the measurement area. In treatment plots that included bedding, soil samples were collected from the bed and in the inter-bed regions, yielding five samples per plot collected on the bed and five samples per plot collected from the inter-bed. All of the inter-bed sampling points were adjacent to the five locations collected on-bed. The soil samples were collected in August 1997 (pre-installation), January 1998 (post-installation), and April 1999 (year 1.5). The soil samples were air-dried and 1-g subsamples were passed through a 2-mm sieve, powdered with a hammermill, and analysed for total carbon and nitrogen on a NA 1500 Carlo Erba C/N/S analyser. The remaining samples were composited by block, treatment, location (bed or inter-bed), and site, resulting in four samples for each treatment/location/site combination.

The soil macro-organic matter in the composite samples was size-density fractionated by the method of Meijboom *et al.* (1995). This method uses an alkaline (pH 10) silica suspension, with the trade name LUDOX (Aldrich Chemical Company), to fractionate macro-organic matter into light, medium, and heavy fractions. The separate fractions represent macro-organic matter at different stages of decomposition, with the heavy fraction being the most decomposed (Tiessen & Stewart 1983; Strickland & Sollins 1987; Meijboom *et al.* 1995). One hundred-gram subsamples from the composited samples were gradually wetted and then flooded with 2 litres of water, thoroughly mixed, and passed through a 150–μm sieve. All the material retained on the sieve was washed into a bucket and separated from the mineral fraction by decanting. The macro-organic matter (>150 μm) was washed on to the 150-μm sieve and then placed in a LUDOX solution adjusted to a density of 1.37 g/cm^3. After being in the solution for 10 minutes, the floating material was skimmed off. The material that remained on the sieve was washed, air dried, and weighed. This fraction is referred to as the heavy fraction. The skimmed material was placed into another 150-μm sieve, and placed in a LUDOX solution adjusted to a density of 1.13 g/cm^3. After 10 minutes, the floating material was skimmed off, washed, air dried, and weighed. This fraction is the light fraction. The remaining material on the sieve was washed, air dried, and weighed and constitutes the medium fraction.

RESULTS

Productive Time Study

The time study data by site for each treatment are summarised in Table 1. Duncan's Multiple Range Test (SAS 1985) was used to compare treatment means within a site and between the same treatments between sites. For both sites, the strip mulch treatment was the most productive. Of the three treatments on the mineral site, the broadcast treatment was least productive.

Since travelling in rows of only 40 m in length is not typical of what a machine would actually do, mean travel speeds for each site/treatment combination were determined and used to adjust productivities as if the machine were operating on a square 8-ha tract. Results of this analysis are summarised in Table 2. Costs were estimated using the machine rate

TABLE 1–Mean elemental time summary for the Rayco T275 operating in 0.16 ha plots.

Treatment	Mineral site				Organic site			
	Travel	Cut	Turn	Total	Travel	Cut	Turn	Total
	(min)				(min)			
Broadcast	29.19	11.89	9.09	50.17a*	–	–	–	–
Soil till	24.78	8.48	8.49	41.75b	24.30	19.91	9.68	53.89a
Strip mulch	17.47	2.29	7.97	27.73c	19.03	12.17	8.54	39.74b

* Means with the same letter are not significantly different using Duncan's Multiple Range Test.

TABLE 2–Production and cost summary for the Rayco T275.

Treatment	Mineral site			Organic site		
	Cost/ SMH	Hectares/* PMH	Cost $/ha	Cost/ SMH	Hectares/ PMH	Cost $/ha
Broadcast	80.80	0.23	437.68	–	–	–
Soil till	80.80	0.28	356.40	80.80	0.21	470.71
Strip mulch	80.80	0.47	216.94	80.80	0.30	337.13

* Productivity based on travel distance of 284 m.

method (Brinker *et al.* 1989). The cost per hectare for the strip mulch treatment on the mineral site was $216.94/ha, which is comparable to conventional costs. Equipment and labour costs associated with conventional mechanical site preparation methods in the south average $195/ha (DuBois *et al.* 1997). This is in-line with the estimated total equipment and labour cost per hectare for shearing and bedding (Table 3) estimated on the mineral site ($196.24). Estimated shearing cost per hectare for the organic site was higher due to such a low productivity (1.02 ha/PMH (Productive Machine Hour)). Bedding production rate for the organic site was assumed the same as for the mineral site, which resulted in a total equipment and labour cost of $301.46/ha.

Pre-treatment data collected on the study plots for each site are summarised in Table 4. Duncan's Multiple Range Test (SAS 1985) was used to compare means between sites. Total

TABLE 3–Production and cost summary for the D7G performing shearing and bedding.

Function	Mineral site			Organic site		
	Cost/ SMH	Hectares/* PMH	Cost† $/ha	Cost / SMH	Hectares/ PMH	Cost $/ha
Shear	106.09	2.62	67.41	106.09	1.02	172.63
Bed	106.09	1.37	128.84	106.09	1.37	128.84
Total	212.18	–	196.24	212.18	–	301.46

* Productivity based on travel distance of 284 m.

† Costs include equipment and labour only and are based on: $316,425 purchase price (V-shear and bedding plough included), 4-yr life, 20% salvage value, 9% interest rate, insurance rate 2% of purchase price, $0.26 per litre fuel cost, lube cost 36.8% of hourly fuel cost, repair & maintenance 100% of annual depreciation, $10 per hour labour rate plus 30% benefits, and 60% utilisation.

TABLE 4—Mean summaries for stump and slash data for the Rayco T275 by site.

Site	Stumps/ ha*	Diameter (cm)	Height (cm)	Mg/ha†
Mineral	1450a‡	18.3a	10.9a	29.41a
Organic	427b	37.1b	16.0b	39.89a

* Includes both pine and hardwood stumps.
† Mg/ha are air dry, 12% moisture content (Wenger 1984).
‡ Means with the same letter are not significantly different using Duncan's Multiple Range Test.

stumps per hectare were significantly lower on the organic site; however, mean stump diameter and height were significantly higher.

Pre-treatment data by treatment for each site are summarised in Table 5. Duncan's Multiple Range Test (SAS 1985) was used to compare treatment means within the same site and between sites. No significant differences were found for the variables listed among treatments within the same site. There were significant differences in stumps per hectare, stump diameter, and stump height for the same treatment when compared between sites.

TABLE 5—Mean summaries for stump and slash data for the Rayco T275 by site and treatment.

Treatment	Mineral site				Organic site			
	Stumps/ ha*	Dia. (cm)	Ht (cm)	Mg/ha†	Stumps/ ha	Dia. (cm)	Ht (cm)	Mg/ha
Broadcast	1245a‡	18.8a	10.2a	27.10a	–	–	–	–
Soil till	1638a	17.8a	10.9a	25.65ab	417b	37.1b	16.5b	52.44b
Strip mulch	1605a	17.8a	11.4a	23.86ab	457b	36.6b	15.0b	30.06b
Conventional	1329a	19.1a	10.9a	41.08ab	408b	38.1b	16.3b	37.21b

* Includes both pine and hardwood stumps.
† Mg/ha are air dry, 12% moisture content (Wenger 1984).
‡ Means with the same letter are not significantly different using Duncan's Multiple Range Test.

For the mineral site, total time was longest for the broadcast treatment, since the machine was required to treat the total area. Of the total time, 58% was spent travelling, 24% was spent cutting stumps, and 18% turning. This translates into a productivity of 0.23 ha/PMH. For the soil till treatment, only about 45% of the area was treated, since beds were on 5.5-m centres. However, the machine had to perform a tilling effect, which adversely affected productivity. Because a smaller portion of the area was treated, this method was more productive than the broadcast treatment at 0.28 ha/PMH. Travelling occupied 59% of the total time, and cutting stumps and turning both occupied 20% of the total time.

For the organic site, applying the soil till treatment was less productive when compared to the mineral site at 0.18 ha/PMH. This lower production rate was due to a combination of two factors. The machine encountered much larger stumps on the organic site (37.1 cm compared to 18.3 cm on the mineral site). In addition, the level of downed woody material on the soil till plots on the organic site was much heavier at 52.44 Mg/ha, compared to 25.65

Mg/ha for the mineral site. Travel time for the soil till treatment on the organic site occupied 45% of the total time; cutting stumps and turning occupied 37% and 18% of the total time, respectively.

For the strip mulch treatment, again, only about 45% of the area was treated. However, since no tilling was being performed, productivity was enhanced and was highest among all treatments at 0.47 ha/PMH. Of the total time, 63% was spent traveling, and only 8% was spent cutting stumps and 29% turning.

For the organic site the strip mulch treatment had a productivity of 0.25 ha/PMH. This lower production rate, when compared to the mineral site, was due mostly to the larger stumps encountered by the machine. Travelling and turning occupied 48% and 21% of the total time, respectively. Cutting stumps accounted for 31% of the total time.

Soil Quality

The implementation of each treatment resulted in a reduction in mean bulk density to a depth of 0.30 m compared to pretreatment levels (CON) with the exception of the surface layer of SMT, BAB, and BNB, and the immediate subsurface layer of BNB (Table 6). A slight increase of approximately 0.18 Mg/m^3 in mean soil bulk density was noted in the surface layer (0.0–0.10 m) of the mineral site of SMT, BAB, and BNB compared to CON, CVN, and SM. The greatest change in soil bulk density from the pretreatment condition occurred in the 0.10–0.2 m soil layer and coincided with the depth of incorporation of mulched material; this was evident in all treatments except BNB. The movement of machine traffic over the site in BNB increased soil compaction in the immediate subsoil layer as indicated by the elevated bulk density. Soil bulk density levels in the 0.20–0.30 m depth of

TABLE 6–Mean soil bulk density (Mg/m^3) and coefficients of variation (%) of surface and subsurface soil layers of a wet pine flat subjected to five tillage treatments, North Carolina.

Soil depth (m)	Treatments*					
	CON	CVN	SM	SMT	BAB	BNB
0.0–0.10	1.01	0.99	1.00	1.18	1.18	1.18
	(32.1)†	(33.9)	(31.4)	(28.9)	(28.1)	(31.2)
0.10–0.20	1.54	1.20	1.26	1.32	1.23	1.57
	(17.0)	(30.0)	(23.5)	(24.2)	(34.5)	(17.6)
0.20–0.30	1.63	1.54	1.48	1.51	1.47	1.55
	(7.9)	(13.9)	(10.5)	(11.4)	(9.6)	(14.0)
0.30–0.40	1.48	1.54	1.49	1.51	1.55	1.49
	(10.6)	(10.9)	(9.2)	(12.6)	(9.3)	(5.5)
0.40–0.50	1.40	1.44	1.36	1.48	1.51	1.44
	(10.2)	(20.0)	(16.8)	(10.8)	(8.1)	(10.5)

* CON = control
CVN = conventional
SM = strip mulch
SMT = strip mulch/till
BAB = broadcast mulch (with bedding)
BNB = broadcast mulch (no bedding)

† coefficient of variation (%)

each treatment remained slightly lower than in CON and BNB but the primary benefit of lowering bulk density occurred in the 0.10–0.20 m depth range. A slight decline in bulk density was observed in the 0.40–0.50 m depth range compared to the overlying soil layers and may be indicative of the formation of a traffic pan at that depth. In general, mean bulk density increased with depth in each treatment and peaked in the 0.30–0.40 m depth in each treatment compared with CON and BNB, which peaked at shallower depths.

Bulk density was reduced in response to tillage treatments at all depths in the organic site with the exception of the upper 0.30 m of the SMT treatment, which was similar to bulk density values of CON (Table 7). Mean bulk density increased with depth in all treatments and appeared to peak in value at the lowest soil depths (0.40 –0.50 cm). The results would indicate a reduction in bulk density in all layers of the soil profile within the organic site in response to CVN and SM treatments, but showed no additional benefit from tilling organic material into subsurface layers (SMT).

TABLE 7–Mean soil bulk density (Mg/m^3) and coefficient of variation (%) of surface and subsurface soil layers of a pocosin site subjected to three tillage treatments, North Carolina.

Soil depth (m)	Treatments			
	CON	CVN	SM	SMT
0.0–0.10	0.41	0.35	0.36	0.41
	(41.7)*	(33.4)	(27.1)	(47.8)
0.10–0.20	0.63	0.56	0.61	0.63
	(23.9)	(29.5)	(27.8)	(36.7)
0.20–0.30	0.78	0.73	0.73	0.80
	(13.4)	(32.8)	(34.9)	(27.2)
0.30–0.40	1.05	0.93	0.83	0.96
	(8.2)	(25.2)	(8.6)	(22.0)
0.40–0.50	1.14	0.91	ND	ND
	(19.2)	(46.1)		

* = coefficient of variation (%)
ND = means of one or two samples only

Gravimetric water contents (GMC) of the mineral site were generally highest in soil surface layers and declined with depth to approximately 0.30 m; a slight increase in GMC occurred below 0.30 m (Table 8). Gravimetric water contents were higher in surface soil layers of CON, CVN, and SM compared to SMT, BAB, and BNB treatments and remained elevated in the 0.10–0.20 m depth in all bedded sites compared to CON and BNB. Soil water contents declined to less than 30% below the 0.20 m depth in all treatments. Gravimetric water contents of the organic site indicated a completely saturated environment in the upper 0.20 m but less water in subsoil layers below 0.20 m (Table 9). Soil moisture status changed with depth, with the highest levels measured in the surface layer and a gradual decline with depth.

The results of an analysis of variance (ANOVA) indicated the main effect of treatment ($p < 0.15$) was not a significant source of variation for bulk density, but depth ($p < 0.001$) and the interaction of depth and treatment ($p < 0.001$) were highly significant in the mineral site. Treatment ($p < 0.05$) and depth ($p < 0.001$) were significant factors in bulk density

TABLE 8—Gravimetric water content (%) (w/w) and coefficients of variation (%) of surface and subsurface soil layers of a wet pine flat subjected to five tillage treatments, North Carolina.

Soil depth (m)	Treatments*					
	CON	CVN	SM	SMT	BAB	BNB
0.0–0.10	51.0	45.4	47.8	33.1	33.9	38.3
	(63.2)†	(43.6)	(49.5)	(36.9)	(34.2)	(42.1)
0.10–0.20	25.1	40.6	35.6	32.3	41.5	21.7
	(49.2)	(49.3)	(38.3)	(49.8)	(56.1)	(22.6)
0.20–0.30	22.3	25.0	26.1	24.4	27.5	22.8
	(29.0)	(22.4)	(15.2)	(18.9)	(22.1)	(13.9)
0.30–0.40	26.8	26.1	26.3	25.1	26.3	27.0
	(13.9)	(24.5)	(14.2)	(18.2)	(22.6)	(8.5)
0.40–0.50	27.7	28.8	28.5	28.0	27.8	29.8
	(14.1)	(18.0)	(13.3)	(18.7)	(9.8)	(9.3)

* = *see* Table 6
† = coefficient of variation (%)

TABLE 9—Gravimetric water content (%) (w/w) and coefficients of variation (%) of surface and subsurface soil layers of a pocosin site subjected to three tillage treatments, North Carolina.

Soil depth (m)	Treatments			
	CON	CVN	SM	SMT
0.0–0.10	166.7	143.5	136.6	140.3
	(28.7)*	(39.2)	(33.4)	(41.4)
0.10–0.20	95.9	96.7	92.2	86.5
	(25.1)	(45.7)	(45.5)	(39.0)
0.20–0.30	73.7	60.8	87.0	57.1
	(20.0)	(29.2)	(17.1)	(31.6)
0.30–0.40	55.6	57.4	61.0	41.1
	(16.4)	(39.5)	(25.8)	(33.9)
0.40–0.50	37.6	47.8	ND	ND
	(17.3)	(37.0)		

* = coefficient of variation (%)
ND = means of one or two samples only

estimations in the organic sites. Depth was the only significant source of variation for gravimetric water contents in both locations.

Cone index (CI) values within each treatment area of the mineral site were generally lowest in the soil surface layer (0.0–0.10 m) and increased with successive depths (Table 10). Reductions in cone index values in the upper 0.20 m from the pretreatment values (CON) were noted as a result of the implementation of each tillage treatment with the exception of BNB. Soil strength remained elevated at all depths in BNB compared to each treatment including CON. The primary benefit of soil strength reduction appeared to be limited to the upper 0.20 m soil layer of each treatment as mean cone index values differed only slightly from pretreatment levels (CON) below 0.20 m. The higher soil strength levels below 0.30-m in all treatments compared with CON may be the result of tillage impacts that extended to

TABLE 10–Mean cone index values (MPa) and coefficients of variation (%) of surface and subsurface soil layers of a wet pine flat subjected to five tillage treatments, North Carolina.

Soil depth (m)	Treatments					
	CON	CVN	SM	SMT	BAB	BNB
0.0–0.10	1.48	0.53	0.54	0.64	0.52	1.73
	(32.2)*	(88.9)	(82.6)	(89.8)	(77.1)	(34.8)
0.10–0.20	1.85	0.82	0.76	1.03	0.74	1.94
	(33.5)	(80.6)	(80.1)	(74.6)	(73.9)	(32.3)
0.20–0.30	1.60	1.43	1.26	1.52	1.46	1.70
	(27.6)	(44.7)	(40.9)	(44.2)	(33.2)	(24.7)
0.30–0.40	1.69	1.92	1.66	2.03	1.86	1.91
	(22.0)	(39.1)	(32.4)	(29.4)	(26.0)	(21.3)
0.40–0.50	1.91	1.80	1.71	1.92	1.87	2.10
	(26.2)	(24.7)	(24.6)	(21.6)	(19.0)	(18.9)

* = coefficient of variation (%)

deeper portions of the soil profile. Peak soil strength levels were achieved in the deeper soil layers of each treatment and may be a reflection of the influence of higher bulk densities and lowered soil moisture contents on soil strength.

Mean cone index values within each treatment in the organic soil site were considerably lower at each depth in comparison to the CON treatment (Table 11). The implementation of each treatment in the organic site lowered mean cone index values from harvested levels, which remained consistent with depth. Mean cone index values were similar at all depths among the treatments under evaluation and exceeded 1.0 MPa only in the lowest depth (0.40 –0.50 m) in SMT.

TABLE 11–Mean cone index values (MPa) and coefficients of variation (%) of surface and subsurface soil layers of a pocosin site subjected to three tillage treatments, North Carolina.

Soil depth (m)	Treatments			
	CON	CVN	SM	SMT
0.0–0.10	0.57	0.20	0.25	0.25
	(32.9)*	(43.5)	(57.9)	(53.4)
0.10–0.20	0.77	0.37	0.35	0.36
	(29.7)	(51.2)	(48.2)	(53.2)
0.20–0.30	0.83	0.58	0.63	0.60
	(28.0)	(40.9)	(38.2)	(49.3)
0.30–0.40	1.00	0.82	0.89	0.85
	(27.6)	(31.0)	(28.9)	(35.7)
0.40–0.50	1.42	0.92	0.90	1.01
	(29.0)	(30.8)	(29.2)	(29.0)

* = coefficient of variation (%)

Soil Carbon

Mean carbon concentrations for each treatment and site for the pre-treatment and post-treatment installation, and 1.5 yr after treatment installation, are shown in Fig. 1. The values shown were from samples collected from the bed, and similar trends were seen for samples

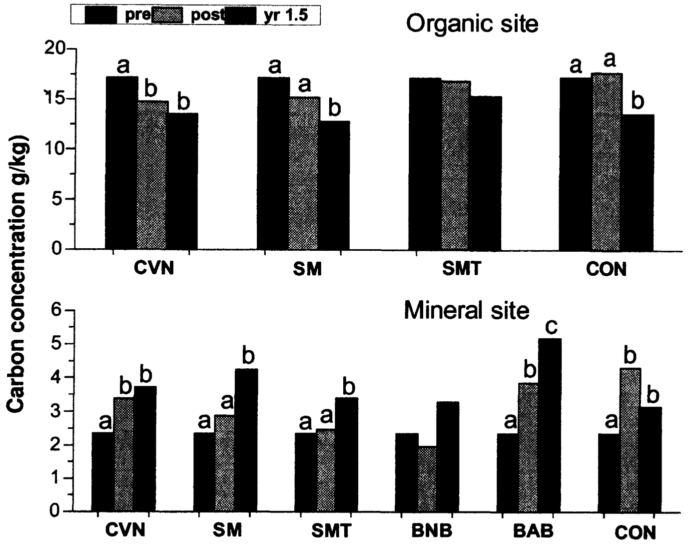

FIG. 1–Mean carbon concentrations for all treatments on the mineral and organic sites. Means with the same letter are not statistically significantly different at the $p \leq 0.05$ level.

collected in the inter-bed (not shown). In the mineral site, the carbon concentration consistently rose with time for all the treatments except the BNB in which there was not a significant change in carbon concentration with time. The opposite trend was seen in the organic site in that, in general, the carbon concentration dropped with time. The soil nitrogen concentration followed similar trends for all the treatments and study sites (Fig. 2). Again,

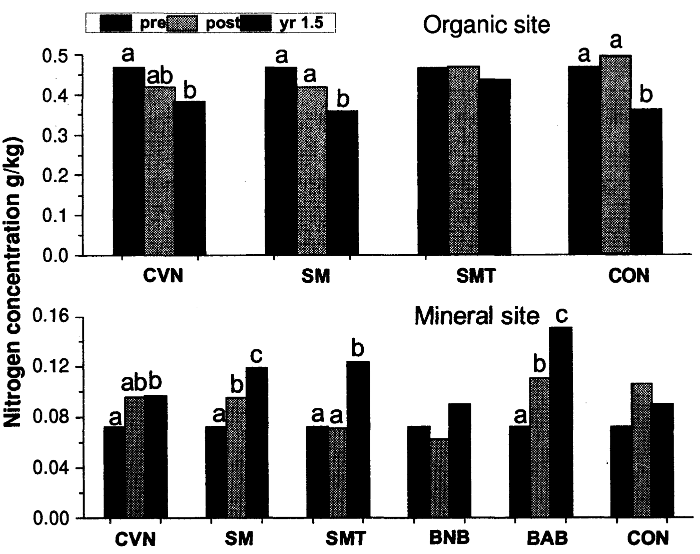

FIG. 2–Mean nitrogen concentrations for all the treatments on the mineral and organic sites. Means with the same letter are not statistically significantly different at the $p \leq 0.05$ level.

the nitrogen concentration increased for all the treatments, except for the BNB and CON, on the mineral site and dropped for all the treatments on the organic site.

The heavy fraction of the macro-organic matter indicates the more humified portion of the macro-organic matter fraction (Tiessen & Stewart 1983; Strickland & Sollins 1987; Meijboom *et al.* 1995). Variations in this fraction may be an early indicator of changes in the soil carbon and soil nutrients with time. Changes in the heavy fraction proportion with time for each treatment and each site are shown in Fig. 3. The light and medium fractions are indications of active carbon and important in carbon turnover studies. However, as this paper focuses on carbon sequestration, the light and medium fractions are not discussed here. On the mineral site, only three treatments (SM, SMT, and BAB) showed significant changes in the heavy fraction. The SMT and BAB treatments showed significant increases with time for the heavy fraction. On the organic site, all the treatments showed significant decreases in the heavy fraction with time. The values shown in Fig. 3 were determined from samples collected from the bed. Unlike the carbon and nitrogen values (Fig. 1 and 2), there was a difference in the heavy fraction dynamics for samples collected in the inter-bed compared with the samples collected on the bed. Changes in the heavy fraction with time for each treatment and each site for samples collected from the inter-bed are shown in Fig. 4. On the mineral site, three treatments (CVN, SM, and SMT) showed significant increases in the heavy fraction with time. On the organic site, there was a general trend towards decreasing proportion of the heavy fraction with time.

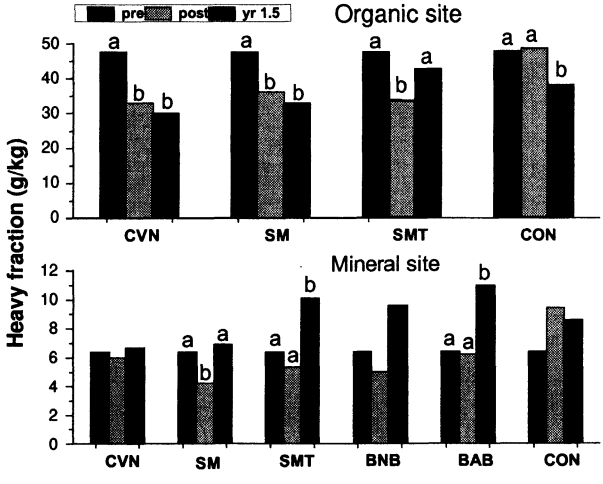

FIG. 3—Mean proportion of the heavy macro-organic matter fraction for all the treatments on the mineral and organic sites. Means with the same letter are not statistically significantly different at the $p \leq 0.05$ level.

DISCUSSION

Productivity Time Study

This study evaluated the performance of a Rayco T275 Hydra-Stumper applying broadcast mulch, strip mulch/soil till, and strip surface mulch treatments on mineral and

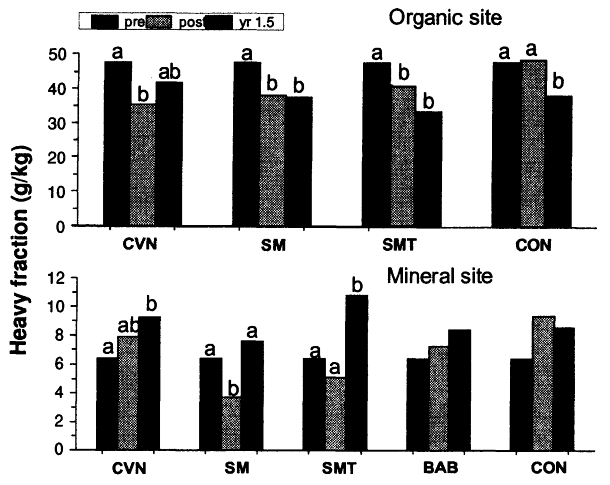

FIG. 4—Mean proportion of the heavy macro-organic matter fraction for samples collected from the inter-bed for all the treatments on the mineral and organic sites. Means with the same letter are not statistically significantly different at the $p \leq 0.05$ level.

organic sites. A conventional system performing shearing and bedding using a CAT D7G crawler tractor was also evaluated for comparison.

The strip surface mulch treatment applied on the mineral site had the lowest cost per hectare. The highest cost per hectare occurred with the strip mulch/soil till treatment on the organic site. All treatments were more expensive to implement than the conventional system. Of the treatments tested, the strip mulch operating under conditions similar to that which existed on the mineral site has the most potential for implementation. To justify using this method over a conventional system, the added benefit, if any, in growth response would have to be determined.

The tillage of surface and subsurface soil layers is considered critical in forest management to enhance regeneration and productivity of pine trees. Management practices that enhance pine productivity on wet pine and pocosin sites have been limited to bedding to provide adequate drainage and aeration for root growth and proliferation. Pine productivity has been significantly improved in bedded sites, especially in locations that are classified as very poorly drained (Cain 1978; Gent *et al.* 1986; Wilhite & Jones 1981). The application of alternative methods of site preparation in sites subjected to extensive periods of wetness has not been extensively reported.

Soil Quality

Beds formed through conventional means are characterised by improved soil physical condition but soil surface layers upon which beds were formed retain the compacted properties evident after harvest (Gent *et al.* 1983; Carter *et al.* 1997). The results of this study were consistent with the previously published studies in which improvements in soil physical properties were noted but confined to the soil within the newly formed beds. The utilisation of the Rayco machine to provide deeper tillage prior to bedding did not confer any advantage over the conventional treatment, as improvements in soil physical properties were evident in all treatments in the upper 0.20 m in both locations. Indeed, soil compaction increased in the immediate subsoil layers of the broadcast and bedded treatment from pretreatment levels and may be related to the additional traffic movement which occurred during the implementation of that treatment. The movement of machine traffic over a harvested tract has the potential to increase soil compaction throughout the soil profile and has been linked to the number of machine passes, axle load, and site conditions (Voorhees *et al.* 1986; Guo & Karr 1989; Murosky & Hassan 1991).

The more intense traffic load related to the broadcasting of mulched materials was noted to result in further compaction of the immediate subsoil layers from the harvested condition but the potential for increased soil compaction status in deeper soil layers existed in response to the implementation of all treatments. Relatively higher bulk density and cone index values below 0.30 m in all treatments in the mineral site compared to control treatments may be an indication that the stresses associated with tillage traffic were transmitted to deeper portions of the profile. Soil compaction status was not affected by tillage treatments in the organic site as bulk density and soil strength remained consistently lower than the control treatments at all depths.

Final soil compaction status may be strongly influenced by site conditions at the time of traffic movement, including soil moisture content, soil texture, and organic matter status. Conditions in the organic site were characterised by higher soil moisture and organic matter status than the mineral site. The consistently lower bulk density and soil strength of the organic site are expected and presumably due to the elevated soil moisture and organic matter content (Ekwue 1990; Greacen & Sands 1980; Thomas *et al.* 1996; Wronski & Murphy 1994).

Soil Carbon

On the mineral site, soil carbon and nitrogen generally increased with time (Fig. 1 and 2), with the BAB treatment showing the largest increase. There was no significant difference between the treatments except for the BAB which showed an almost 100% increase in soil carbon and nitrogen after 1.5 years compared with the pre-treatment installation values. Since there was a significant difference between the BNB and BAB treatments but no difference between the SM and SMT treatments, it appears that bedding incorporated the mulched forest slash but the effect of tilling was not yet evident at 1.5 years. However, since there were changes in the soil physical properties that may alter decomposition rates, it is probable that the effect of tilling on soil carbon and nitrogen will become more evident in later years. On the organic site, there was no significant difference between the treatments, suggesting that the observed decrease in soil carbon and nitrogen was probably a result of the disturbance during harvesting and treatment installation.

When one is determining the potential of the treatments to contribute to carbon sequestration and increasing soil nutrient levels, the bed and inter-bed regions should be considered separately. The two regions represent two significantly different microclimates, with the inter-bed region generally having a higher bulk density and soil moisture level and lower soil temperature than the bedded region. These soil characteristics should have major implications for the forest slash and soil organic matter decomposition rates. Although there was no observed difference in the soil carbon and nitrogen values between the bedded and inter-bed regions, there was a significant difference in the decomposing macro-organic matter (Fig. 3 and 4). On the mineral site, only the SMT treatment showed consistent increases in the heavy fraction, suggesting that this treatment will continue to have an influx of carbon and nutrients into the soil. Although the BAB treatment showed the largest increase in the heavy fraction in the bedded region (Fig. 3), it did not show significant changes in the inter-bed region. Thus, it is probable, considering the effects of the treatments on the stand level, that the SMT and the BAB treatments will sequester carbon and increase soil nutrients at similar levels. Because the other treatments had lower carbon and nitrogen increases and lower (or non-significant) increases in the heavy fractions in the bedded and inter-bed regions, they will not be as effective in sequestering carbon and increasing soil nutrients as the BAB and SMT treatments. There is no evidence that any treatment had a positive effect on carbon and nitrogen sequestration on the organic site and should not be considered as a part of the management of this site or sites similar to it.

CONCLUSIONS

This study suggests that the incorporation of forest slash as a means to sequester carbon, increase soil nutrient levels, and improve soil physical properties is a realistic possibility. Comparison of the mineral and organic sites showed that the incorporation of forest slash does not always yield improved soil chemical and physical properties (e.g., the organic site), which raises the question as to which soil types would benefit from organic matter incorporation. Another area of this study is the development of carbon and nutrient budgets. This is currently being done with the collection of soil carbon dioxide efflux, soil nutrient, and soil water data. This study is still in its infancy and there remains the question of whether the observations will persist. Additionally, there is the question as to the availability of the sequestered carbon and the associated nutrients on different soil types. The answer to these and related questions will probably not be available for a few more years. Although currently financially unpalatable, increased utilisation of the Rayco T275 Hydra-Stumper (or similar machinery) for site preparation activities should lower costs associated with mulching and residue incorporation. Lower site preparation costs coupled with the potential increases in site productivity and the desire to collect carbon credits for sequestering carbon would make the incorporation of forest slash a viable site preparation option.

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