Effect of Ditching, Fertilization, and Herbicide Application on Groundwater Levels and Groundwater Quality in a Flatwood Spodosol[1]

D. S. Segal, D. G. Neary, G. R. Best, and J. L. Michael*

ABSTRACT

Groundwater levels and associated water quality parameters were studied in a young slash pine (*Pinus elliottii* Engelm.) plantation following ditching, fertilization, and herbicide application. Drainage ditches surrounding each watershed significantly lowered groundwater levels up to 45 m from the ditch for mean and high water table conditions. Drainage ditches were not deep enough to significantly influence groundwater levels during drier periods. A seasonal pattern in nutrient migration to the groundwater was exemplified by NH_4-N, NO_3-N, K, Ca, and Mg. Concentration of each nutrient was greatest in July following a dry spring. Potassium was the only nutrient which increased significantly in the groundwater due to fertilization. The herbicide sulfometuron methyl [methyl 2-[[[L(4,6-dimethyl-2 pyrimidinyl)-amino] carbonyl] amino] sulfonyl] benzoate] was not detected in any groundwater samples.

Additional index words: **Ammonium, Calcium, Drainage, Magnesium, Nitrate, Nutrients, Oust, *Pinus elliottii* Engelm., *Pinus taeda* L., Potassium, Sulfometuron methyl, Florida.**

Intensive silvicultural activities, such as draining seasonally wet areas, fertilizing, and applying pesticides, have been used for many years to increase pine (*Pinus* spp.) growth in southeastern forests (Pritchett, 1979; Duncan and Terry, 1983). Neary et al. (1985) found slash (*Pinus elliottii* Engelm.) and loblolly pine (*Pinus taeda* L.) seedlings growing on a flatwood Spodosol doubled in size following fertilization. Pine growth also doubled after application of the herbicides sulfometuron methyl and glyphosate [N-(phosphonomethyl) glycine], and tripled from the combined application of fertilization and herbicide. Water control structures, usually drainage ditches or tile drainage, are often used to drain seasonally wet soils in forested conditions (Pritchett, 1979; Duncan and Terry, 1983). Objectives of drainage are generally to 1) improve roads for better site access; 2) increase early survival of planted seedlings; and 3) increase growth and reduce rotation age (Hewlett, 1972). Because the surficial water table ranges from 15 to > 200 cm below ground in poorly drained flatwood soils. intensive forestry activities potentially alter the water table depth and flow pattern as well as water quality. Associated with intensive forestry practices comes the possibility of diminishing water quality as silviculture in Florida moves toward agricultural intensity levels (Riekcrk, 1982).

Mobility, persistence, and fate of fertilizer nutrients and pesticides as nonpoint-source pollution are subjects of scientific and ecological interest, (Neary, 1985; Rirkerk, 1982; Bengtson, 1981). Nonpoint-source contributions to the groundwater seem minor when compared to isolated point-source contamination. However, cumulative effects of nonpoint-source pollution may he as or more significant than concentrated point-source contamination. Therefore, it is important to assess the environmental impacts associated with intensive forest management practices to gain a better understanding of the alterations which may result across large regions.

The objectives of this research were to determine effects of ditches on surficial groundwater levels and fertilization and herbicide applications on water quality in a flatwood Spodosol. Assessment of these impacts with regard to water quality will provide information useful in prudent silvicultural resource management.

METHODS

Site Description—The study site, owned by Container Corporation of America, is located 13 km north of Gainesville, FL. Mature slash pine were harvested from the site in late 1983 by clearcut logging. Following site preparation, I-yr-old slash and loblolly pine seedlings were planted. Herbaceous and woody plants such as saw palmetto (*Serenoa repens* Barrram), gallberry (*Ilex glabra* L. Gray), chalky bluestem (*Andropogon capillipes* Nash-S), and blueberry (*Vaccinium stamineum* L., *V. myrsinites* 1 .am.) have colonized the landscape.

Three watersheds (WS), each approximately 100 m x 500 m, were constructed by dredging a ditch circumferencing each WS (Fig. 1). The ditches, roughly 'L-m-deep by 3-m-wide, provided a drainage outlet for each WS and prevented horizontal movement of surface and subsurface water from one ws to another. The dominant soil type in each WS is Pomona sand (sandy, siliceous, hyperthermic Ultic Haplaquod). This soil is characterized as nearly level

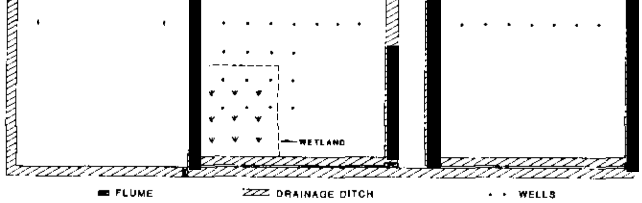

Fig. 1. Site layout indicating location of watersheds, sampling wells, and flumes.

[1]Fla. Agric. Exp. Stn. Journal Series No. 7942.

[2]Formerly graduate student, Environmental Engineering Sciences. Present address: Savannah River Ecology Laboratory, Aiken, SC 29801; adjunct professor, USDA Forest Service and Soil Science Department; associate director, Center for Wetlands; and research chemist, USDA Forest Service, Auburn, AL 36849.

and poorly drained. The spodic (Bh) and argillic (Bt) horizons impede vertical water movement. Water permeability tends to he rapid to very rapid in the surface horizons and moderately slow to moderate in the lower part (Thomas et al., 1985). These wits are sufficiently droughty during dry seasons to impose moisture stress on vegetation hut are saturated during wet seasons.

Well Installation—Seven piezometric welts were installed approximately 15 m apart in a transverse pattern through each of the three WS (Fig. I). Additionally, 12 more wells were constructed in and adjacent to the wetland zone in WS 5. Wells consisting of 5-cm-diameter, netted polyvinylchloride (PVC) pipe were extended approximately 2 m into the ground. The netted pattern of this pipe facilitates unobstructed water movement into the well. Each well was capped at the bottom to preclude capillary rise of the water table. Piezometric wells were encased at the surface by a IO-cm, solid PVC pipe which extended approximately 15 cm into the ground to prevent surface water from entering directly into the well.

Measurement of Water Table Depths—Water table depth was measured at each well on a weekly or more frequent basis. These measurements continued over a 6-m" period and encompassed both extremely wet and extended dry periods. The entire study site was surveyed to determine elevation of each well and ditch above a reference benchmark.

Water-table depth was measured from the top of each well and related to a surveyed benchmark. This technique was used because the wit surface was disturbed during mechanical site preparation. Three hydrological conditions across the study site were recognized: mean high water level, mean water level, and mean low water level. A multiple linear regression (SAS, 1082) was used to estimate groundwater level in relation to ditch location.

Treatment—In March 1 985, WS 4 and 5 were fertilized with a balance of macro- and micronutrients at *224* kg ha^{-1} (Table 1). In July 1985, both WS 4 and 5 were treated with sulfometuron methyl at 114 g ai ha-'. Groundwater sampling commenced 2 weeks (wk) after application of herbicide. WS 6 received no treatment and was maintained as a control. Water samples were extracted from each well throughout the study with a bailer pump. Samples were originally collected at 2-wk intervals but then ~-educed to a more infrequent schedule when groundwater levels dropped below the bottom of the welts.

At time of sampling, each well was first pumped out to remove standing water. After the well refilled, 500 mL of water was collected for sulfometuron methyl determination and 100 mL for nutrient analyses. Water samples were analyzed for NH_4-N, NO_3-N, PO_4-P, K. Ca, and Mg. A $Ca(PO_4)_2$ buffer was immediately added to the herbicide water sample to stabilize the solution (Michael, pers. cm.). Water samples were then placed on ice until transferred to a freezer later in the day.

Concentrations of NI L-N, NO,-N, and PO_4-P were determined using colorimetric procedures in an automated analyzer (Technicon Industrial Systems, 1977, 1978) and K, Ca, and Mg by use of an inductively-coupled argon plasma (ICAP) spectrophotometer. Sulfometuron methyl concentration was detemined by HPLC (unpublished DuPont method).

Mean nutrient concentration of seven wells from each WS was compared to determine effects of treatment, location, and time. These calculations were conducted using an analysis-of-variance procedure (SAS, 1982). Additionally, an analysis of variance was used to compare nutrient concentration among treatment and control WS for each sampling date.

RESULTS AND DISCUSSION

Cursory observations revealed that mean groundwater level was higher in the central portion of each WS and declined toward the ditches (Fig. 2j. This observation follows trends reported by Duncan and Terry (1983). To further investigate the ditching influence on ground water level, each well was

Table 1. Nutrients added in fertilizer blend.

Elements	Amount	Concentration†
	kg ha^{-1}	mg kg^{-1}
N	33.6	13.4
P	13.4	5.4
K	28.0	11.2
Ca	** ‡	** ‡
Mg	5.6	2.2
Mn	0.27	0.1
Fe	** ‡	** ‡
Cu	0.28	0.1
Zn	0.40	0.2
B	0.15	0.1
S	11.2	4.5
Mo	0.03	0.01

†Concentration of element per hectare 15 cm plow depth (assume bulk density = 1.65 g cm^{-3}).
‡Analysis not available.

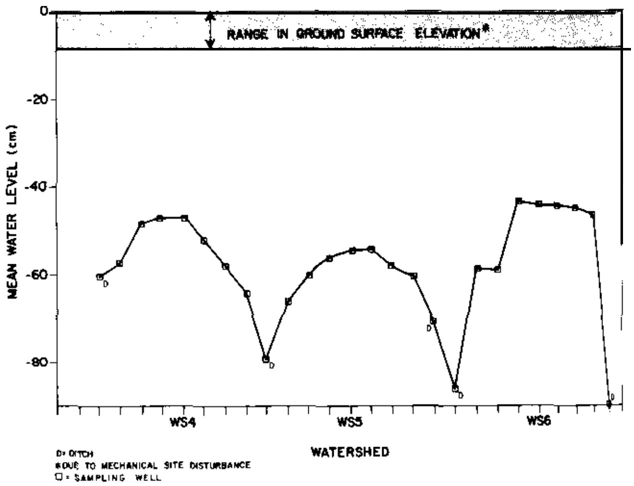

Fig. 2. Mean water table height at each sampling well for Watershed 4 (WS4), Watershed 5 (WS5) and Watershed 6 (WS6). *Sampling wells are located 15 m apart along the study transect in each WS.*

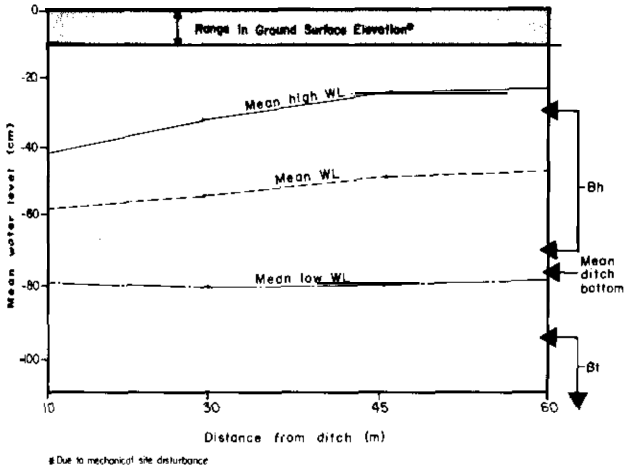

Fig. 3. Mean high water level, mean water level, and mean low water level as influenced by distance of wells from drainage ditch.

categorized by distance from nearest ditch. The categories, 10 m, 30 m, 45 m, and 60 m, each contained two wells from each WS except the 60 m category which had only one well from each of the three WS.

Ditching influence on groundwater level was studied for three hydrological conditions: mean water level, mean high, and mean low water level (Fig. 3). Drainage ditches significantly reduced groundwater level in the flatwoods under both mean high and mean water level. Draw down of the water table was most, apparent within 4.5 m of the ditch. Ditches were ineffective in further reducing the water table level during extended dry periods (low water level) when groundwater level dropped below the depth of the ditch bottom. Rainfall was the only significant variable ($P \leq 0.05$) influencing water table level during extended dry periods.

Nutrient Concentration in Groundwater

Concentration of NH_4-N increased in all three WS through the summer and then declined to presumably background levels in [anuary (Fig. 4). This seasonal increase of NH_4-N in summer months in both treatment and control WS can he attributed to stimulatory effects from pronounced wetting and drying cycles (Morris and Pritchett, 1982; Morris, 1981), higher mineralization rates of forest-floor litter. and higher soil temperatures (Lowrance et al., 1984; Peterjohn and Correll, 1983; Morris and Pritchett, 1982; Morris, 1981). Increased mineralization rates have been reported to occur in similar soils following tree harvest and site preparation (Morris, 198 1). Mineralization results from incorporation of slash material and partially decomposed organic matter deeper into the soil.

Mean Nf L-N concentration was significantly higher in WS 4 during the summer peak months (Fig. 4). This WS was the more poorly drained of the two treated WS as observed by higher mean groundwater levels (Fig. 2) and a predominately gleyed argillic

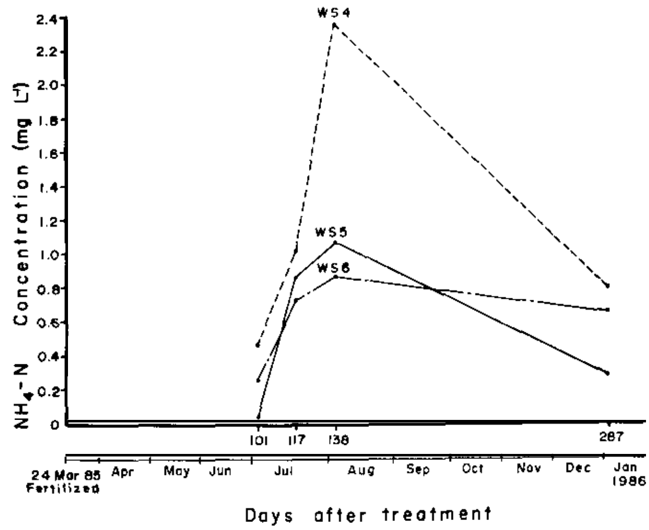

Fig. 4. **Mean NH_4-N** concentration for Watershed 4 **(WS4)**, Watershed 5 **(WS5)** and Watershed **6 (WS6)** at sampling dates following fertilization. (Each point is the mean of seven wells.)

horizon. Accumulation of NH_4-N occurs under anaerobic conditions due to suppressed nitrification rates in soil zones which are devoid of oxygen (Reddy and Patrick, 1984; Ponnamperuma, 1972). After measuring inorganic N concentration in soil solution, Morris (1981) found a greater concentration of NH.,-N in the poorly drained Mascotte soil and a greater concentration of NO_3-N in the moderately well-drained Stilson soil. He attributes this partitioning effect to inhibition of ammonification in the acidic Mascotte soil. The Stilson soil, on the other hand, has a higher pH which promotes complete nitrification. Lowrance et al. (1984) also found elevated NH.,-N concentration in the wettest soils located nearest streams.

Concentration of NO_3-N exhibited a seasonal increase through the summer in WS 5 and 6, hut fluctuated over- time in WS 4 (Fig. 5). Groundwater con-

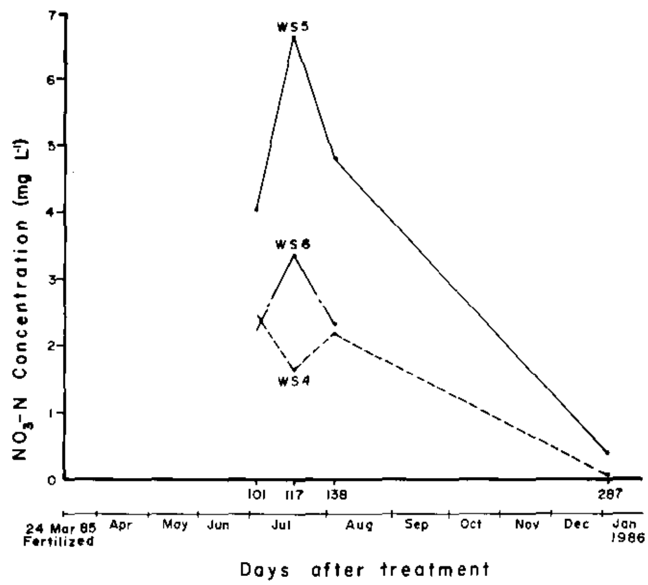

Fig. 5. Mean NO_3-4 concentration for Watershed 4 (WS4), Watershed 5 (WS5) and Watershed 6 (WS6) at sampling dates following fertilization. (Each point is the mean of seven wells.)

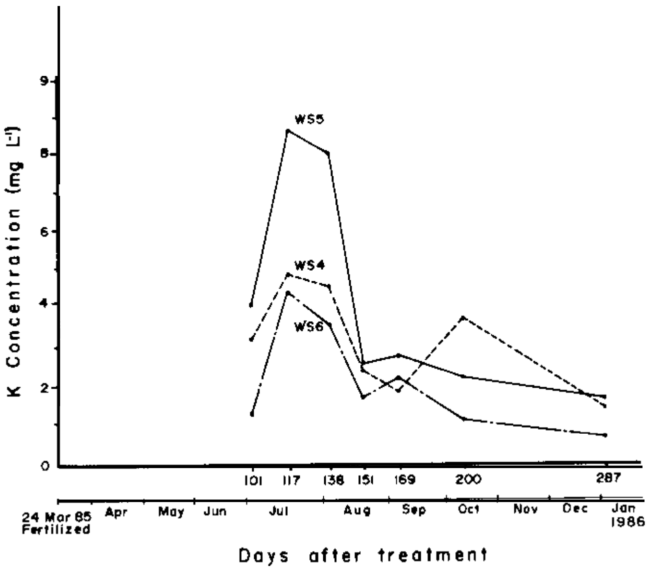

Fig. 6. Mean K concentration for Watershed 4 (WS4), Watershed 5 (WS5) and Watershed 6 (WS6) at sampling dates following fertilization. (Each point is the mean of Seven wells.)

centration of NO,-N was significantly higher in WS 5 during July and August. This WS was the best drained WS as observed hy lower mean groundwater levels (Fig. 2) and many high chroma, oxidized mottles in the argillic horizon. Because nitrification is the biological oxidation of NH,-N, first to NO,-N and then to NO_3-N, nitrification occurs only in the presence of oxygen (Reddy and Patrick, 1984; Reddy et al., 1980; Patrick and Dulaune, 1972; Gambrell and Patrick, 1978). Nitrate then becomes quite stable in the presence of oxygen (Rowell, 1981).

Potassium concentrations in the groundwater were significantly higher in the treatment WS at I I7 d after fertilization (daf) (Fig. 6). Potassium also exhihited a seasonal pulse in July in all three WS. Potassium is structurally unbound in plant tissue and consequently quite mobile in forest ecosystems (Morris and Pritchett, 1982). Seasonal changes are also common because K is quite soluble (Waring and Schlesinger, 1985). In a study of nearby soils, a seasonal K pulse was observed (CRIFF Progress Report, 1973-74). Highest concentration occurred in spring and declined following onset of the rainy season in June. A high aount of variation associated with K determinations was also reported. Lowrance et al. (1984) noted patterns similar to those reported by CRIFF (1973-74) by finding higher concentrations of K during April through June and a decline during July through September. They attributed these seasonal dynamics to fertilizer application and subsequent crop uptake of nutrients.

Calcium concentrations in the groundwater were elevated in all three WS up to 138 daf (Fig. 7). There was a significant change in concentration of Ca with rime, hut no significant difference among fertilized and control WS. Because the intermediate concentration of Ca was found in the groundwater of the control WS, a seasonal pulse of Ca through mid-July appeared ubiquitous on-site. Lowrance et al. (I 984) observed a similar seasonal pulse of Ca in groundwater wells from April through June. Higher Ca concentrations were observed in all three WS in June and July when groundwater levels were elevated due to high rainfall. Ponnamperuma (1972) reports that Ca concentration in soil solution increases in low O_2 systems when more mobile, reduced ions such as Fe'-, Mn^{2+}, and NH_4^+ displace Ca^{2+} on the exchange sites.

Magnesium concentration in the groundwater showed a seasonal high in July in both treated and control WS (Fig. 8). Concentration declined in August in each WS and remained suppressed throughout the fall. Seasonal dynamics of Mg were reported to peak in spring by Lowrance et al. (1984). Concen-

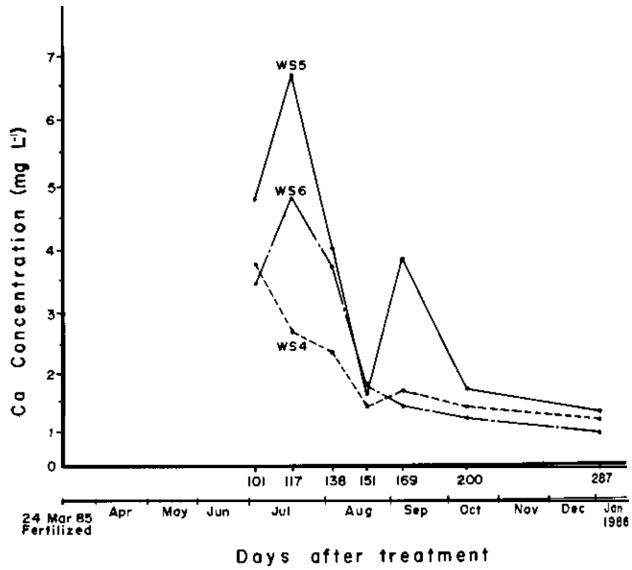

Fig. 7. Mean Ca concentration for Watershed 4 (WS4), Watershed 5 (WS5) and Watershed 6 (WS6) at sampling dates following fertilization. (Each point is the mean of Seven wells.1

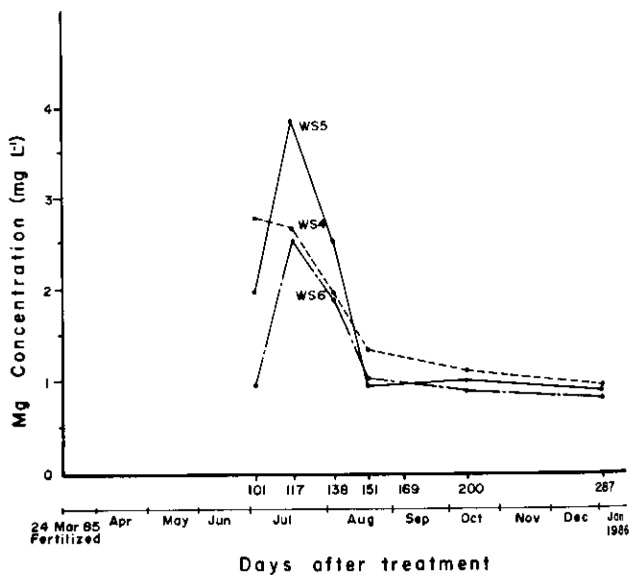

Fig. 8. Mean Mg concentration for Watershed 4 (WS4), Watershed 5 (WS5) and Watershed 6 (WS6) at sampling dates following fertilization. (Each point is the mean of seven wells.1

tration of Mg in soil solution in nearby soils varied with soil depth and time but were nor influenced by fertilization treatment (Voss, 1975).

There was no significant difference in PO_4-P concentration presumably due to the high variance among WS and sampling times. Lowrance et al. (1984) reported no seasonal P pattern in groundwater wells and Morris and Pritchett (1982) detected nonsignificant changes in P concentration between site preparation methods. They believe adsorption/desorption was more important in determining P availability rather- than decomposition of organic matter (OM).

Herbicide Concentration in Groundwater

Sulfometuron methyl is currently used for controlling broadleafweeds and many annual and perennial grasses on noncropland areas such as rights-of-way. In silvicultural studies, it has been used to control herbaceous species in young pine plantations without causing increased pine mortality (Clason 1984; Michael 1983; Neary et al. 1984). Research indicates that h'igher soil adsorption of sulfometuron methyl occurs in acidic soils with high OM (DuPont unpublished). Half-life is estimated at < 1 wk during the growing season at the Gainesville study site. Degradation occurs primarily by hydrolysis, photolysis, and microbial action.

Sulfometuron methyl:' was not detected in the groundwater (detection limit = I $\mu g\ L^{-1}$), throughout the 5 mo of investigation. Although potential leaching could occur in the sandy, permeable soil (Rao et al., 1983),a short half-life and rapid degradation may prevent leaching of sulfometuron methyl to the groundwater. Additionally, the presence of two hardpan layers, a spodic and an argillic horizon, may increase soil adsorption and minimize leaching.

SUMARY AND CONCLUSIONS

Drainage ditches reduced groundwater levels within 45 m of the ditch during mean and high rainfall periods. Water levels were unaffected by ditches > 45 m from ditches and during drier periods. A significant seasonal pulse of NH_4-N, NO_3-N, K, Ca, and Mg occurred in July in both fertilized and control WS. This seasonal pulse was probably due to increased microbial activity, high rainfall, and incorporation of slash material and OM in the soil from prior tree harvest and site preparation. Total inorganic N was highest in the two treated WS hut the dominant N species appeared to be contingent on groundwater hydrology of each WS. Concentration of NH,-N was highest in the wettest, fertilized WS and NO-N was highest in the driest, fertilized WS. There was no detectable pattern in PO_4-P concentration. Sulfometuron methyl was not detected in any groundwater samples.

[3]Manufactured by E. I. DuPont de Nemours and Co., Inc., under trade name of Oust at 75% ai. Use of trade names does not constitute endorsement by USDA or the University of Florida, but is used for a reference only.

'The delayed seasonal occurrence of nutrients in the groundwater in July rather than in spring as reported hy others (Lowrance, 1984; Morris, 1981: CRIFF, 1973-74) can probably be attributed to drought conditions encountered in late spring and early summer. With the exception of K, the absence of a pronounced fertilizer treatment effect is probably due to the low concentration of fertilizer added (224 kg ha-') combined with high vegetative density w-site. The concentration of nutrients found in the groundwater appear to be part of the natural seasonal dynamics occurring at this site. The addition of fertilizer and herbicide did not appear to adversely alter groundwater quality.

ACKNOWLEDGMENTS

We acknowledge E. 1. DuPont de Nemours and Co., Inc., and Container Corporation of America for their support. Michael C. Allen, USDA Forest Service, was extremely helpful with data collection and D. A. Graetz, University of Florida Soil Science Department, offered valuable editing suggestions.

LITERATURE CITED

Bengtson, G. W. 1981. Nutrient conservation in forestry: A perspective. South. J. Appl. For. 5:50-58.

CRIFF Progress Report. 1974. Soil Science Dept., Univ. of Fla., Gainesville.

Duncan, D. V., and T. A. Terry. 1983. Water managent. *In* The managed slash pine ecosystem. Proc. Symp. Univ. of Fla., Gainesville.

Gambrell, R. P., and W. H. Patrick, Jr. 1978. Chemical and microbiological properties of anaerobic soils and sediments. *In* D. D. Hook and R. M. M. Crawford (Ed.), Plant life in anaerobic environments. Ann Arbor Sci., MI.

Hewlett, J. D. 1972. An analysis of forest water problems in Georgia. Ga. For. Res. Council Rep. 30. 27 pp.

Lowrance, R. R., R. L. Todd, and L. E. Asmussen. 1984. Nutrient cycling in an agricultural watershed: I. Phreatric movement. J. Env. Qual. 13:22-27.

Michael, J. L. 1983. Growth of loblolly pine treated with hexazinone, sulfometuron methyl, and metsulfuron methyl for herbaceous weed control. South. J. Appl. For. 9:20-26.

Morris, L. A. 1981. Redistribution and mobilization of nutrients as a result of harvest and site preparation of a pine flatwoods forest. Ph.D. thesis, Univ. of Fla., Gainesville. 190 pp.

Morris, L. A., and W. L. Pritchett. 1982. Nutrient storage and availability in two managed pine flatwoods forests. Pp. 17-26 *In:* Impacts of intensive forest management practices symposium, 9-10 March 1982.

Neary, D. G. 1985. Fate of pesticides in Florida's forests: An overview of potential impacts on water quality. Soil Crop Sci. Soc. Fla. Proc. 44:18-23.

Neary, D. G., L. F. Conde, and J. E. Smith. 1984. Effects of sulfometuron on six important competing species in coastal plain flatwoods. Proc. South. Weed Sci. Soc. 37:193-199.

Neary, D. G., T. E. Cooksey, N. B. Comerford, and P. B. Bush. 1985. Slash and loblolly pine response to weed control and fertilization at establishent. Proc. South. Weed Sci. Soc. 38:246-253.

Patrick, W. H., Jr., and R. D. Dulaune. 1972. Characterization of the oxidized and reduced zones in flooded soil. Soil Sci. Soc. Am. Proc. 36:573-576.

Peterjohn, W. T., and D. L. Correll. 1984. Nutrient dynamics in an agricultural watershed: observations on the role of a riparian forest. Ecology 65:1466-1475.

Ponnamperuma, F. N. 1972. The chemistry of submerged soils. Adv. Agron. 24:29-96.

Pritchett, W. L. 1979. Properties and management of forest soils. John Wiley and Sons, USA.

Rao, P. S. C., R. S. Mansell, L. B. Baldwin, and M. F. Laurent. 1983. Pesticides and their behavior in soil and water. Soil Sci. Fact Sheet. SL 40. IFAS, Univ. of Fla., Gainesville.

Reddy, K. R., and W. H. Patrick, Jr. 1983. Effects of aeration on reactivity and mobility of soil constituents. Chemical mobility and reactivity in soil systems. Soil Sci. Soc. Am. J. 11:11-33.

Reddy, K. R., and W. H. Patrick, Jr. 1984. Nitrogen transformations and loss in flooded soils and sediments. CRC Critical Reviews in Environmental Control 13:273-309.

Reddy, K. R., and W. H. Patrick, Jr., and R. E. Phillips. 1980. Evaluation of selected processes controlling nitrogen loss in a flooded soil. Soil Sci. Soc. Am. J. 44:1241-1246.

Riekerk, H. 1982. Water quality management in flatwoods of Florida. *In* Coleman, S. L., A. C. Mace, and B. F. Swindel (Ed.), Impacts of intensive forest management practices symposium, 9-10 March 1982. Univ. of Fla. pp. 53-67.

Rowell, D. L. 1981. Oxidation and reduction. *In* The chemistry of soil processes. D. J. Greenland and M. H. B. Hayes (Ed.), John Wiley and Sons, Ltd.

SAS user's guide. 1982. SAS Institute, Inc., Cary, N.C.

Technicon Industrial Systems. 1978. Nitrate and nitrite in water and wastewater (range 0.04-2.0 mg n/l) (1978 rev.) Ind. Meth. 100-70 W/B. Tarrytown, NY. 3 pp.

Technicon Industrial Systems. 1977. Individual/simultaneous determination of nitrogen and/or phosphorus in BD acid digests. Ind. Meth. 329-74 W/B. Tarrytown, NY. 9 pp.

Thomas, B. P., E. Cummings, and W. H. Wittstruck. 1985. Soil survey of Alachua County, Florida. SCS-USDA.

Voss, R. L. 1975. Potassium cycling in a fertilized slash pine ecosystem in Florida. Ph.D. thesis, University of Florida, Gainesville. 133 pp.

Waring, R. H., and W. H. Schlesinger. 1985. Forest ecosystem concepts and management. Academic Press, Orlando, FL.

Soil Penetrometer Resistance and Peanut Responses to Tractor-Wheel Compaction in Sandy Soil[1]

F. P. Gardner, A. Selamat, and R. S. Mansell[2]

ABSTRACT

Soil compaction and associated restriction of root growth is a common problem on sandy soils in southeast U.S., presumably due to repeated mechanized field operations. The objective of this study was to determine the relationships among tractor-wheel compaction, changes in soil strength, and peanut (*Arachis hypogaea* L.) growth. Effects of tractor-wheel compaction on the distribution of soil penetrometer resistance (soil strength) in the soil profile and peanut growth and yield were investigated. Two types of sandy soils, Lakeland sand (Thermic Quartzipsamment) and Arrendondo loamy sand (Grossarenic Paleudult) were used in 1982, 1983 and 1986. At each location, root growth was restricted by a tillage layer having soil strength > 2.5 MPa from 0.3 m to a maximum depth of 0.45 m. Plants in heavy traffic areas were stunted and yellow. Tractor-wheel compaction increased penetrometer resistance at all depths in the sampled soil profile (0 to 0.5 m), and this effect appeared to be accumulative with time. One or more tractor-wheel passes over the planter row significantly increased soil strength, especially in the upper 0.3 m of the profile, and decreased peanut total dry matter (TDM), pod, and seed yields. Mounding loose soil over the compacted row increased TDM and pod yields by 6 and 9%, respectively. The percentage of seeds with undesirable small size was increased by compaction. We conclude that agricultural machinery traffic on the surface of sandy soils can increase soil strength by compaction, which results in restricted peanut root and pod growth.

***Additional index words:* *Arachis hypogeae*, Soil compaction, Soil penetrometer, Root restriction, Hardpan, Florida soils, Subsoiling.**

Repeated use of agricultural machinery, particularily power-driven types, may increase soil compaction (Voorhess et al., 1978), restrict root growth (Taylor et al., 1966), and reduce crop yield (Campbell et al., 1968).

Voorhees (1977) reported that the effective land area covered by tractor-wheel tracks from tillage during a single season may completely cover twice the tilled area. Depth of ruts in sand-dune soil can increase up to 19 cm linearly with the logarithm of the number of passes (Jakobsen and Greacen, 1985), and the elastic limit can be easily exceeded in sandy soils, resulting in structural failure and compaction (Volk, 1953). Initially loose soils are particularily affected, and the first pass of a wheel has a greater effect than succeeding passes (Soane et al., 1981). Residual effects due to compaction may remain in a soil indefinitely (Burmister, 1965).

The soil penetrometer is an effective means to assess compaction, mechanical impedance, or soil strength (Gerard et al., 1982; Gill, 1968; Soane et al., 1981a; Volk, 1953). Values between 1.7 to 2.8 MPa have been observed to impede corn (*Zea mays* L.) root growth (Fiskell et al., 1968; Taylor et al., 1966; Voorhees, 1984). Increasing soil water content has been shown to decrease penetrometer resistance such that soil strength fluctuates during the growing season as soil-water content varies due to rainfall and evapotranspiration (Rhoads and Wright, 1981; Robertson, 1984).

Rhoads (1978) showed that soil-penetrometer measurements at 0.15 to 0.2 m depth under soybean (*Glycine max* L. Merr.) rows were about 2.0 MPa less in subsoiled plots compared to no subsoiling and also increased the 2-yr average soybean yield by 27% (745 kg ha^{-1}). Parker et al. (1976) found that subsoiling a sandy loam soil increased soybean yields. The benefits of subsoiling depended on soil type (Touchton et al., 1984).

Recently, Vasquez-Palaios (1986) observed that penetrometer measurements in profiles of Florida Arredondo fine sand (Grossarenic Paleudult) increased with depth to a maximum of 2.6 and 3.1 MPa at 0.45 m and decreased at greater depths, indicating the presence of a restricted zone (tillage pan) at about

[1]Fla. Agric. Exp. Stn. Journal Series No. 8008.

[2]Professor and graduate student, respectively, Agronomy Department, and professor, Soil Science Department, University of Florida, Gainesville, FL 32611.