# Visually Determined Soil Disturbance Classes Used as Indices of Forest Harvesting Disturbance

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**ABSTRACT:** *Visual estimates of soil and site disturbances are used by foresters, soil scientists, logging supervisors. and machinery operators to minimize harvest disturbances to forest sites, to evaluate compliance with forestry Best Management Practices (BMPs), and to determine the need for ameliorative practices such as tnechanical site preparation. Although visual estimates are commonly used by field personnel, the actual relationships of visually determined soil disturbance classes to various soil physical properties and site characteristics have not been determined The purpose of this investigation was to evaluate if visually determined soil disturbance classes ore related to quantitative soil and site properties that are known to influence soil productivity and hydrologic function. Several types of quantitative data were evaluated within the soil disturbance classes: static data (bulk density, saturated hydraulic conductivity, total, capillary, noncapillary pore space, and soil roughness) and dynamic data (mechanical resistance, volumetric soil moisture, subsurface water table depth). All data were collected from a long-term forest productivity study located in the Coastal Plain of South Carolina The study is a randomized complete block design with two harvest disturbance levels (wet-weather harvest vs. dry-weather harvest) and a maximum of five site soil disturbance (SD) classes. Disturbance classes included undisturbed (SDO), compressed but not rutted (SDI), rutted (SD2), deeply rutted (SD3), and churned (SD4).*

*Analyses revealed that three static variables (soil bulkdensity, saturated hydraulicconductivity, macropore pore space) and two dynamic variables (depth of the subsurface water tabk and mechanical resistance) were significantly related to disturbance. Although undisturbed and compressed areas generally were affected less than the more severe disturbance classes, the three most severe disturbance classes, churned areas, deeply rutted areas, and rutted areas were not different from one another. Thus, it appears visual disturbances do not necessarily equate to site damage. The overall implications are that visually determined soil disturbance classes have merit as indices of some soil and site changes, but they should not be equated to soil damage categories. South. J. Appl. For. 22(4):245–250.*

**Vehicular traffic associated with forest harvesting operations has the potential to compact and/or puddle forest soils (Hatchell et al. 1970, Aust et al. 1993, Scheerer et al. 1995). Although a wide variety of site and machinery factors influence soil disturbances, the likelihood of soil disturbance is enhanced on moist to saturated soils**

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(Moehring and Rawls 1970, Greacen and Sands 1980, Aust et al. 1995). Wet flats, referred to regionally as wet flatwoods, pocosins (not true pocosins), or bays have flat topography and poor internal drainage. When wet flats are subjected to fire or site preparation, they are dominated by pine species; wetter, less disturbed wet flats have a larger hardwood component (Harms et al. 1998). In the southeastern United States, fairly even seasonal distribution of rainfall in some years and very intense rainfall associated with hurricanes, tropical depressions, and even thunderstorms, combined with the relatively flat topography and poor drainage of the wet pine flats frequently result in site disturbance. Compared to undisturbed sites, compacted and puddled wet pine flats often have increased soil bulk density, decreased macroporosity and hydraulic conductivity, and elevated volumetric water content, resulting in impeded drainage conditions and inadequate soil oxygen for root respiration (Lockaby and Vidrine 1984, Aust et al. 1995). Growth declines of pine species on those disturbed sites may be attributed to the decreased soil aeration caused by the soil physical changes (Hatchell et at. 1970, Langdon 1976. Hatchell 1981, Karr et al. 1987).

Several researchers have suggested that such disturbances may have long-term consequences for the management of pine plantations (Foil and Ralston 1967, Scheerer et al. 1995, Tiarks and Haywood 1996). Concern about potential site degradation issues associated with soil compaction and rutting are evidenced by the Sustainable Forestry Initiative by industrial forest companies (American Forest and Paper Association 1994, 1996); the development of forestry best management practices by states in the southeastern region (Aust 1994); andcontinued efforts to define and quantify forest soil health and develop indices that can be successfully used to predict forest productivity (Burger 1996). Unfortunately, the most thoroughly understood indices of soil disturbances and site productivity are labor-intensive, require large sampling time frames, and are unfamiliar to many foresters and logging supervisors. The purpose of this research is to compare and relate both static and dynamic variables that have been successfully used to quantify site disturbance with a fast, simple method of soil disturbance classification.

## Indices of Forest Harvest Disturbance

Harvest-induced disturbances have been characterized by a variety of quantitative and qualitative measures, but most are used to quantify the ease with which roots can penetrate the soil and/or the movement of air and water in the soil. Intact soil cores are commonly collected to determine more than one-aspect of soil disturbance. Intact soil cores can be used to sample soil bulk density (Blake and Hartge 1986), which has been used toquantify soil compaction by forestand agricultural researchers for decades (Greacen and Sands 1980). Gale et al. (1991) evaluated limiting soil bulkdensities for white spruce over a wide range of soil textures and concluded that spruce root growth was limited by bulk densities between 1.46 and 1.84 Mg/m$^3$.

The intact soil cores used for soil hull, density samples can also be used to determine total pore space, soil microporosity, and soil macroporosity, which are indices of soil aeration and drainage (Danielson and Sutherland 1986). Finally, the intact cores are often used to measure saturated hydraulic conductivity, an index of soil water movement and potential soil drainage problems (Klute and Dirksen 1986). These techniques have been successfully used to characterize forest soil disturbance for a variety of situations in the southeastern Coastal Plain, including harvesting machinery-soil interactions (Aust et al. 1993, McDonald et al. 1995), effects of harvesting and site preparation on soil properties and tree growth (Gent et al. 1983, Tiarks and Haywood 1996), and effects of thinning during wet periods on subsequent stand growth (Karr et al. 1987, Reisinger et al. 1988; 1993). However, these intact soil core sampling techniques are almost invariably used to characterize research plots, as opposed to being used for forest management and planning applications. The techniques are relatively laborious and time consuming, and intact soil cores are very difficult to acquire during saturated soil conditions or after soils have been puddled. These difficulties as well as technology advances have persuaded forest managers and researchers to investigate the use of additional soil/site characterization pnramsters. Examples include soil strength measurements as facilitated by recording penetromerers. measurements of near surface groundwater via newer types of stage recorders, and almost instantaneous measurements of volumetric soil water contents via Time Domain Refractometry (TDR) (Burger 1994)., as indices of soil disturbance, although these types of technology are relatively expensive as compared to soil cores.

At present, no quantitative method of accessing site disturbance has been developed that can be used for common forestry applications. Therefore qualitative methods have been developed. Over the decade, numerous studies have attempted toquantify thespatial disturbances associated with wet-weather timber harvests and many of these studies have used modifications of the spatial soil disturbance classes originally developed by Miller and Sirois (1986). The various modifications of the soil disturbance classes generally include some recognition of soil litter layer disturbance, obvious soil compression caused by traffic, soil ruts caused by traffic, and mixing of mineral and litter layers.

## Methods

### Study Site

The study site on which this research took place is a typical low-lying, wet pine flat on marine and fluvial deposits in the lower Coastal Plain of Colleton County, South Carolina. Prior to harvest, a 20 yr old loblolly pine *(Pinus taeda)* plantation, operated by Westvaco Corporation, occupied the site. Understory species included red maple *(Acer rubrum)*, water oak *(Quercus nigra)*, willow oak *(Q. phellos)*, cherrybark oak *(Q. pagoda)*, sweetgum *(Liquidambar styraciflua)*, and palmetto *(Sabal* spp.). Soils within the study site are classified 2s Typic Ochraqualfs and Typic Umbraquults, poorly drained soils with massive subsoil structure and slow permeability.

Table 1. Average bulk density, saturated hydraulic conductivity, and total, micro-, and macropore space for each soil disturbance (SD) class within each harvest condition for sites within the Coastal Plain of South Carolina. (Values followed by different alphabetic letters are significantly different at P-values ≤ 0.05.)

| Harvest conditions | SD | Bulk density ($Mg/m^3$) | Saturated hydraulic conductivity (cm/h) | Total pore space | Micropore space | Macropore space | Roughness coefficient |
|---|---|---|---|---|---|---|---|
| | | | | ........................ | (%) | ........................ | |
| Dry harvest | 0 | 1.24 a | 10.1 c | 51.5 | 37.7 | 13.9 c | 0.783 |
| Dry harvest | 1 | 1.38 ab | 4.3 b | 48.4 | 38.6 | 9.8 b | 0.799 |
| Wet harvest | 0 | 1.26 a | 8.9 b | 50.9 | 38.0 | 13.0 c | 0.812 |
| Wet harvest | 1 | 1.44 b | 1.6 ab | 41.2 | 39.3 | 7.9 ab | 0.865 |
| Wet harvest | 2 | 1.46 b | 0.6 a | 47.6 | 40.7 | 6.9 a | 0.848 |
| Wet harvest | 3 | 1.48 b | 0.4 a | 48.5 | 42.7 | 5.8 a | 0.867 |
| Wet harvest | 4 | 1.46 b | 1.2 a | 48.4 | 41.8 | 6.6 a | 0.864 |

### Treatments

Prior to treatment installation, Burger (1994) collected soil and site data to ensure that the sites had uniform hydrology, soil, and vegetation. Treatment plots were arranged in a randomized complete block design with three blocks. Each of the three blocks contained two harvest disturbance treatments (wet-weather harvesting and dry-weather harvesting). Each harvest treatment plot contained 6.4 ha (16 ac). Dry-weather harvest treatments were installed during September 1993; wet-weather harvest treatments were installed in March 1994. Each treatment was harvested with typical harvesting systems, including a rubber-tired feller buncher and rubber-tired skidder. Following harvests, Preston (1996) visually classified soil disturbance within a5 m radius around 80 points (25 points/ha) within each wet-harvest and dry-harvest treatment plot. Soil disturbance classifications were as follows:

i. Soil Disturbance Class 0 (SDO). The soil appeared to be undisturbed by traffic.

ii. Soil Disturbance Class 1 (SD1). The soil was obviously compressed by vehicular traffic, but no ruts were formed.

iii. Soil Disturbance Class 2 (SD2). The soil was rutted (as evidenced by puddled soil) and the rut depth measured < 0.20 m (8 in.).

iv. Soil Disturbance Class 3 (SD3). The soil was rutted (as evidenced by puddled soil) and the rut depth measured ≥ 0.20 m (8 in.).

v. Soil Disturbance Class 4 (SD4). The soil was obviously churned and puddled with indications of liquid soil movement.

After soil disturbance classes were assessed, standard cylindrical soil cores (2.54 cm radius x 5.08 cm length) were collected with a double cylinder bulk density hammer as described by Blake and Hartge (1986). Soil core samples were randomly selected so that 12 subsamples were collected from each combination of block (3), harvest regime (2), and soil disturbance class. All five disturbance classes occurred and were sampled in the wet-harvest treatments. However, only two disturbance classes occurred in the dry-harvest treatment (SD0 and SDI) so only two disturbance classes were sampled. Each reported value for treatment and soil disturbance class (Tables 1 and 2) is an average of 36 values (3 blocks x 12 samples/treatment). These soil cores were used to determine values for soil bulk density (Blake and Hartge 1986). saturated hydraulic conductivity (Klute and Dirksen 1986), total porosity, microporespace, and macropore space (Danielson and Sutherland 1986). Open. 3 cm diameter water wells were installed at the points and measured bimonthly so that average water table depths below the soil surfacecould be determined (Reeve 1986). A modification of the method proposed by Saleh (1993) was used to measure soil roughness on the site. Saleh (1993) recommended use of a roller chain for measurement of soil roughness, but such a chain was deemed impractical for the very wet and muddy conditions of the study site. Rather, soil roughness estimates were made by placing a 1/4 in. link loggingchain having a 6.1 m (20 ft) length over an exposed soil surface. This length corresponds to the size of the area evaluated for determining the original soil disturbance classes. The chain was carefully placed in a straight line and then fitted to thecontours of the soil surface, each link was extended to its maximum length, and the horizontal distance between the origin of the chain and its endpoint was measured. The ratio of fitted surface length to extended horizontal length was calculated and

Table 2. Average values of dynamic site/soil variables for each soil disturbance (SD) class within each harvest condition for sites within the Coastal Plain of South Carolina. (Values followed by different alphabetic letters are significantly different at P-values ≤ 0.05.)

| Harvest conditions | SD | Depth to subsurface water table (cm) | Volumetric soil moisture (%) | Mechanical resistance (MPa) |
|---|---|---|---|---|
| Dry harvest | 0 | 20.1 b | 39.3 | 0.541 a |
| Dry harvest | 1 | 20.6 b | 47.5 | 1.120 b |
| Wet harvest | 0 | 20.2 b | 38.1 | 0.630 ab |
| Wet harvest | 1 | 18.6 b | 51.5 | 0.532 a |
| Wet harvest | 2 | 14.1 a | 37.9 | 0.507 a |
| Wet harvest | 3 | 14.6 a | 48.1 | 0.501 a |
| Wet harvest | 4 | 17.2 ab | 50.4 | 0.668 ab |

termed roughness coefficient. Volumetric water content was estimated using Time Domain Reflectometry (TDR) in the soil range of 0.0 to 0.45 m depth; soil strength was estimated with a Rimik CP 20 cone penetrometer with a cone diameter of 12 mm, inserted manually to a depth of 0.45 m and recorded in 0.025 m increments (American Society of Agricultural Engineers Standards 1992).

## Results And Discussion

### Area Within Each Soil Disturbance Class

The differences between wet- versus dry-weather timber harvest disturbance are shown by the disturbance classes detected within each treatment and by the percentage of area that was classified in each soil disturbance class (Preston 1996). Wet-weather harvesting causes disturbances ranging from undisturbed (SDO) to churned (SD4). while dry-harvest areas weredisturbed by compaction (SD1) only. Only 13% of wet-weather harvested areas was undisturbed (SDO), while 94.8% of the dry-weather harvest areas was undisturbed (SDO). In general, these results reflect a higher level of disturbance than reported for harvests in other wet pine flats, whichrangedfrom 17% to 48% of the harvested area (Hatchell et al. 1970. Willis 1971, Dickerson 1976, Aust et al. 1993). However, these previous studies may have occurred under different soil moisture regimes and used different soil disturbance classification systems and methods.

### Soil Disturbance Class and Static Soil Properties

In general, the soil disturbance classes were good indicators of change in relatively static soil physical properties such as bulk density, saturated hydraulic conductivity, and macropore space (Table 1). As soil disturbance class increased (became more severe), bulk density increased and saturated hydraulicconductivity and macroporosity decreased. On wet-harvested areas, compaction (SDl) increased bulk density from 1.26 to 1.44 $Mg/m^3$, saturated hydraulic conductivity dropped from 8.9 to 1.6 cm/hr, and macroporosity dropped from 13.0 to 7.9%. Additional disturbance (SD2, SD3, and SD4) had no further effect on these properties. The same trend held true for total and micropore space and roughness coefficient, but the differences were not significant. Saturated hydraulic conductivity values dropped from 3- to 8-fold, indicating greatly impeded soil drainage. Aeration porosity was reduced below 10% by all disturbance types, a level associated with inadequate soil gas exchange for root respiration (Childs et al. 1989). Disturbed bulk density values ranged from 1.38 to 1.48 $Mg/m^3$, approaching rooting limiting values reported by Gale et al. (1991) and Childs et al. (1989).

The increases in soil bulk density and the concomitant decreases in macropore space and saturated hydraulic conductivity are similar to results reported for trafficked wet pine flats in other research studies (Hatchell et al. 1970, Tippett 1992, Aust et al. 1993, Scheerer 1994). The total pore space and micropore space did not change significantly following disturbance, a pattern that has been found on other wet flat sites. The roughness coefficient was hypothesized to be sensitive to sitedisturbances. It has been used for agricultural applications (Saleh 1993). However, agricultural fields generally have less variable surfaces and less variation in microtopography than compared to these forest sites that were bedded 20 yr previously. Romkens and Wang (1986) identified four scales of surface roughness: microrelief variations due to aggregates, surface variations due to cloddiness (random roughness), directional roughness due to tillage implements (oriented roughness), and landscape variation. Random roughness is reported to be detectable on the centimeter scale, while oriented roughness exists on the meter scale (Zobeck and Onstad 1987). The scale of roughness detectable with a chain on a forest site may be that which is due to oriented roughness, or roughness due to ridges and clods formed during tillage, but it appears to lack the sensitivity to distinguish random roughness associated with harvesting disturbances.

### Soil Disturbance Class and Dynamic Soil Properties

Analyses of variance shows that the dynamic site/soil variables (depth of subsurface water table, volumetric soil moisture, and soil strength as measured by mechanical resistance) were differentiated by certain soil disturbance classes (Table 2).

We hypothesized that the volumetric soil water content would increase with compaction and with lower aeration porosity. This was probably the case. but differences were not significant at the 0.05 level of probability. Compaction (SD1) had no effect on the water table depth, but greater levels of disturbance due to rutting and churning (SD2, SD3, and SD4) decreased saturated hydraulic conductivity to less than 1.2 cm/hr, which slowed subsurface water flow and drainageand resulted in less depth to water table. Soil strength doubled on compacted areas of dry-harvested plots, but decreased or stayed the same with disturbance on wet-harvested plots as volumetric water content increased. Soil strength is largely a function of volumetric water content. Disturbance increased bulk density and field-capacity wafer content of both dry- and wet-harvested plots, but soils had higher strength only on compacted areas of dry-harvested plots. This may be a function of different compaction mechanisms of dry vs. wet soils. Compaction of soils on dry-harvested plots followed typical compression, while a combination of compaction, puddling, and churning formed compacted soils of the wet-harvested areas.

## Conclusions

The soil disturbance classes used by Preston (1996) to describe harvest traffic effects on flatwoods sites are easily identified by most foresters and equipment operators and are easily related to machine performance. Soil compaction (SD1) is compression without soil flow that occurs when soil macropores are collapsed. Soil rutting (SD2 and SD3) occurs at higher volumetric moisture approaching the liquid limit when soil flows under pressure. The distinction between a shallow (<0.2 m) and deep rut (>0.2 m) is soil flow associated with distinctly different soil layers or horizons that have very different physical and mechanical properties. Churned soils (SD4) reflect nearly total coverage by deeply (>0.2 m) churned disturbance. These data show that easily discernible soil disturbance classes should not be thought of in terms of a disturbance severity gradient even though the soil disturbance classes appear to represent different disturbances. Spatial disturbance is not synonymous with damage. For example, compaction (SD1) is hardly discernible in some cases, but the SD 1 values for bulk density, macroporosity, and saturated hydraulic conductivity are nearly as great as that of deeply rutted (SD3) and churned soils (SD4), primarily because water filled pores are difficult to compact. On the other hand, compaction has little effect on water table increases, while shallow rutting increases the water table and dramatically restricts subsurface water flow. In soils with deep subsurface clay horizons, much deeper ruts and churning have little or no further effect on these hydrologic properties despite the fact that the spatial extent of their disturbance is much greater.

Therefore, as pointed out by Preston (1996), no generalization can be made about the severity of soil damage based on a gradient of spatial disturbance. Furthermore, no generalizations can be made about the relative usefulness of static versus dynamic soil properties as indicators of soil damage, except that static properties best define compaction effects and dynamic properties best define puddling effects. Even if soil roughness measurements were better correlated with spatial disturbance as defined by soil disturbanceclasses, it would be a poor indicator of soil damage because a numerical gradient of soil damage is not correlated with most static and dynamic soil properties associated with soil productivity and hydrologic function.

Soil and site damage from vehicular traffic is best judged by: (1) the effect of soil compaction on increased soil strength of dry to moist soils (10% to 50% Field Capacity), (2) the decrease in aeration porosity below 10% in soils that are repeatedly saturated during the growing season, and (3) the decrease in hydraulic conductivity of wet soils, or soils that are frequently saturated, to the extent that saturated hydraulic conductivity impedes normal soil drainage of poorly to somewhat poorly drained sites.

The results of this study show that compaction (SD I) is a good indicator of change in soil strength when soil moisture contents are low. Furthermore, any rutting, no matter how severe (SD2, SD3, SD4) is an indicator of possible hypoxia, or decreased soil aeration for biological respiration. Finally, any rutting or puddling could decrease soil drainage, increase mean annual water tables, and change soil productivity relationships and hydrologic function.

The five soil disturbance classes used to index disturbance regimes within the wet- and dry-harvested sites corresponded well to several of the static soil physical and the dynamic soil and site properties. Overall, these results have several implications:

1. Soil disturbance classifications are fast, simple, and inexpensive indices of static soil physical properties.
2. Calculating a soil roughness coefficient, an attempt to quantify spatial disturbance, was neither useful for describing spatial disturbance, nor useful as an indicator of static or dynamic soil and site properties.
3. The soil disturbance classifications used on this site may be overly differentiated, the static soil physical property values indicate that SD3-SD4 might be combined.
4. Although some soil disturbance classes are obviously related to static and dynamic soil properties, soil disturbance classes alone should not be considered an accurate index of changes in soil productivity and. hydrologic function

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