

CRITERIA 4. INDICATOR 22
AREA AND PERCENT OF FOREST LAND WITH SIGNIFICANT COMPACTION OR
CHANGE IN SOIL PHYSICAL PROPERTIES RESULTING FROM HUMAN
ACTIVITIES

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A. RATIONALE

Soil is a complex mixture of air, water, mineral material, and organic matter. The balance among these components largely determines the ability of the soil to support plant life. Soil compaction occurs when the mineral portion of the soil becomes compressed by equipment, reducing pore space and decreasing the volume of air in the soil. Under severe compaction, soil aggregates may be destroyed, resulting in “puddling” or the loss of soil structure by particles being dispersed in water and then settling to form a dense crust.

Compaction can have a variety of effects on soil productivity resulting from changes in both physical and chemical properties. Reduction in pore space makes the soil more dense and difficult to penetrate and can constrain the size and extent of root systems. In severe cases, this reduced rooting volume can lead to structural failure of the plant support system and destabilization of the entire tree. Reduction in the amount and continuity of macropores can reduce infiltration rates (Greacen and Sands, 1980) and the flow of air and gases through the soil

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(Cannell, 1977), reducing the ability of roots to absorb water, nutrients, and oxygen. At the landscape scale, destruction of soil structure can limit water infiltration sufficiently to increase rates of runoff and soil loss from erosion. In addition to changes in soil physical properties, compaction can also significantly impact biological and chemical processes occurring in the soil. By reducing the soil oxygen content below that required for adequate respiration, severe compaction can disrupt root metabolism and shift the soil towards an more anoxic condition. Although forest soils are dynamic, where root growth and soil fauna activity will often reverse some of the effects of soil compaction, changes to soil physical properties can have a significant impact on forests for years following disturbance (e.g., Froelich et al., 1985).

Compaction varies greatly in nature and depends on physical properties and the moisture content of the soil. In general, the risk of compaction increases with increasing moisture, with the greatest sensitivity to compaction occurring at moisture contents that are near but below field capacity (Fisher and Binkley, 2000). For example, field measurements suggest that compaction may be 4 to 5 times greater at 15 percent moisture content than at 5 percent moisture content (Fisher and Binkley, 2000; Froelich and McNabb, 1984). Similarly, under comparable conditions, soils with a range of soil particle sizes (e.g., fine sandy loam) are generally more susceptible to compaction than soils with a more uniform particle size distribution. In these soils, disturbance causes the finer soil particles to fill the larger macropores formed by the coarse particle fraction, producing a denser soil. Although finely textured soils can hold more water per unit volume, the effects of compaction may be less permanent in these soils because of shrinking and swelling in response to wetting and drying (Fisher and Binkley, 2000).

The purpose of this indicator is to quantify the extent of human induced changes to the physical properties of forested soils that are of sufficient magnitude to adversely affect soil fertility, hydrology, and/or other ecosystem processes or cause significant reductions in site productivity. However, it is not within the scope of this data report to provide a detailed discussion of the potential impacts of compaction on forest productivity. Rather, the objective is limited to: (1) identifying nationally-consistent sources of data that can be used to help quantify this indicator, and (2) providing an initial analysis of soil compaction estimates collected as part of the Forest Inventory and Analysis and Forest Health Monitoring programs. As with other soil indicators, the effects of compaction on forest health and productivity vary between different systems and the term “significant” needs to be defined with respect to variation between different landscapes and soil types.

B. DATA USED TO QUANTIFY THE INDICATOR

Although methods for measuring changes in soil physical properties exist at the research scale, there are no widely accepted standards of what constitutes significant compaction. One of the most direct indices of soil compaction is a measure of the ratio between the weight of solid particles and the total volume of soil, or bulk density. Another useful index of potential limitations to root growth is soil strength as measured by cone penetrometer. However, at present, no national level datasets exist to quantify soil strength at anything other than the research scale.

This report combines two different approaches for estimating the potential extent of compaction on forested lands. First, the sensitivity of woodland soil units to management practices will be

assessed using woodland equipment limitation ratings derived from the NRCS STATSGO (State Soil Geographic) soils database. These results will then be compared to initial estimates of compaction and bulk density measured on Forest Inventory and Analysis/Forest Health Monitoring plots.

B.1 Woodland Equipment Limitation Ratings

The USDA Natural Resources Conservation Service (NRCS) is responsible for collecting, storing, maintaining, and distributing soil survey information for privately owned lands in the United States. The NRCS has established three soil geographic databases that are produced at different intensities and scales of mapping. Each database has a common link to an attribute data file for each map component. The State Soil Geographic database (STATSGO) is a 1:250,000 map that was designed primarily for regional and multistate interpretations (USDA NRCS, 1994). Details of the STATSGO database structure and the aggregation method employed in this analysis may be found in Appendix A. Documentation and metadata for STATSGO may be found at: http://www.ftw.nrcs.usda.gov/stat_data.html.

In the context of soil survey, woodland ecological sites are separated from rangeland ecological sites based on the historic climax plant community that occupied the site before the arrival of European settlers. An Ecological Site Type of "woodland" is assigned where the historic vegetation was dominated by a 25 percent overstory canopy of trees, as determined by crown perimeter-vertical projection. A tree is defined as a woody-stemmed plant that can grow to 4 meters in height at maturity (National Soil Survey Handbook, NRCS). Woodland soils are then assigned to a woodland group that is comprised of soils that are suited to the same tree types,

similar production potential, and similar hazards and limitations for management. The equipment limitation rating represents the probability that soils may be negatively impacted as a result of site preparation and the aftermath of cutting operations. A risk category of *slight* indicates that the use of equipment is not limited to a particular type of equipment or time of year; *moderate* indicates a short seasonal limitation or a need for some modification in equipment or management; and *severe* signifies a seasonal limitation, a need for specialized equipment or management practices, or a potential hazard in the use of equipment (National Soil Survey Handbook, NRCS). To develop an estimate of the sensitivity of soils to physical disturbance resulting from management activities, equipment limitation ratings for individual soil components were assigned a numerical rating code. Spatially weighted averages of equipment limitation ratings were then determined for each map unit and the weighted data from each state compiled into a single national map (Figure 22.1). Potential limitations associated with the aggregation scheme are provided in Appendix A.

Slope, slope stability, and soil moisture are major considerations in rating soils for equipment operability (National Soil Survey Handbook, 2001). Sensitivity of soils to physical disturbance tends to be associated with areas of high clay content, seasonally high soil moisture content, and/or steep slopes. In general, soils in the eastern United States were characterized as more sensitive to physical disturbance following the use of equipment, with the majority of severely rates soils located in the Northern and Southern Resources Planning Act (RPA) regions. The lower limitation ratings in the interior west may also be attributed, in part, to the aggregation scheme used for producing this map (Appendix A); because limitation ratings are assigned only

for woodland soil components but aggregated over the entire map unit, map units that contain a large portion of “non-woodland” (e.g., rangeland) soils will tend to have a lower severity rating.

B.2 FIA/FHM Soil Measurements

Compacted Area

Parameters for monitoring soil compaction were developed and initially measured by the Forest Health Monitoring program in the 1990’s. In 1999, they were transferred to FIA and now are a subset of the FIA sample grid, with one forest health plot for every 16 standard plots (Stolte et al., 2002). When fully implemented, soil variables will be collected on approximately 7,800 plots measured over a 5-year cycle. Variables used to assess soil erosion are based primarily on assessments of exposed bare soil, plant cover, forest floor thickness, soil texture, and slope. These field data are then combined with ancillary data on climate and landscape position to parameterize soil erosion model inputs. Documentation of the FIA/FHM sampling design and field methods may be found at <http://fia.fs.fed.us/library.htm>.

Compaction data collected as part of the FHM program from 1999-2000 were based primarily on visual assessments of compacted areas and crew assessments of the type of compaction associated with compacted areas. At each subplot, crews used five main criteria to delineate compacted areas: (1) a change in density from nearby undisturbed soil, (2) presence of coarse platy structure, (3) formation of ruts in the soil, (4) loss of normal structure, compared to nearby undisturbed soil, and (5) formation of mottles in the soil (blotches of different color interspersed with the dominant color that indicate a change in the oxidation status of the soil). Other evidences of compaction were recorded as part of the plot notes. Changes in density were

determined by using a tile probe to assess the relative difference in soil density between compacted areas and adjacent uncompacted areas. If evidence of compaction was found, the area of the subplot in percent exhibiting this evidence was recorded. Finally, crews recorded a description of the type or types of compaction observed.

Figure 22.2 summarizes the spatial distribution of compaction estimates. During 1999 to 2000, only 272 of the 2006 plots measured for the soils indicator (14 percent) reported compaction on more than 5 percent of the plot area. However, of those plots, the majority (60.8 percent) reported compaction on less than 10 percent of the plot (Fig. 22.3). Only 1.6 percent of the total number of plots measured in these two years (33 plots) measured reported compaction on greater than 50 percent of the plot area. The majority of plots reporting compaction (81%) showed one or two evidences. Only one plot had five different evidences of compaction and no plots showed all six possible evidences. Of the six possible evidences, increased density was the most common observed (48%), followed by loss of soil structure (20%) and ruts present (17%). Mottling was the least common evidence observed (< 1%). Because these results are based on visual estimates, these values reflect both the frequency of these evidences and the ease with which they can be detected.

For each subplot that showed compaction, the crews were asked to identify a compaction type or types to describe the subplot. Compacted trail was the most common compaction type recorded (48.1 percent) followed by rutted trail (19.8 percent) and compacted area (18.9 percent). Although the majority of plots (67.9 percent) showed only one compaction type, two or more compaction types were identified on more than 164 plots.

Bulk Density

In FIA, bulk density is determined by using an impact-driven coring device to collect a sample of known volume from a pre-assigned soil sampling location. Samples from the 0-10 cm and 10-20 cm soil layers are collected in stainless steel, cylindrical core liners that are 4 inches long and have an internal diameter of 2 inches. Samples are sent to one of three regional labs for determination of sample weights, moisture, and coarse fragment (> 2mm) content. Bulk density is then calculated as:

$$\text{Bulk Density (g cm}^{-3}\text{)} = \text{g Oven Dry Soil} / \text{Core volume (181 cm}^3\text{)}$$

Coarse fragment content is measured by sieving air-dried mineral soil samples through a 2-mm mesh and weighing the > 2mm fraction. This weight is expressed as a percentage of the total air dry sample weight and reported separately in the database. Total organic soil carbon is measured on a subsplit of the < 2 mm fraction by dry combustion. Results are expressed as a percent of air-dry sample weight.

Bulk density data from the 2000 and 2001 field seasons are presented in Figure 22.4. Averaged across all plots, the mean bulk density for the 0-10 cm soil layer was $1.01 \pm 0.32 \text{ g cm}^{-3}$ (n = 1520). Bulk density values were highly correlated with organic carbon content for the 0-10 cm cores, suggested that samples towards the lower end of the bulk density range may be a result of the incorporation of some O-horizon materials (Fig, 22.5). Mean bulk densities measured for the 10-20 cm layer were significantly higher at $1.32 \pm 0.30 \text{ g cm}^{-3}$ (n = 1516; two-tailed T test, P <

0.0001). Only 5.8 percent of the 0-10 cm samples (88 out of 1520 samples) had a measured bulk density greater than 1.5 g cm^{-3} . Crews were not able to collect volumetric soil cores on all plots due to differences in soil texture, rock content, and accessibility that prevent use of the bulk density corer. In 2000-2001, volumetric cores were not collected on 23 percent of the 0-10 cm cores.

C. INTERPRETATION

Given the spatial distribution of the existing data, it is not currently possible to quantify the extent of U.S. forestlands experiencing compaction. However, data from the NRCS STATSGO database and the FHM soil indicator program can provide some general insights into the susceptibility of different regions to physical disturbance associated with forestry equipment. Although soils throughout much of the eastern U.S. are rated as more susceptible to physical disturbance from management practices (Fig. 22.1), evidence of surface soil compaction above trace levels (≥ 5 percent of plot area) was not found on the majority of FHM plots measured in 1999-2000 (86 percent). However, soil compaction may still pose a serious problem at the local level as indicated by the presence of more than one type of compaction on individual plots and the high proportion of compacted area reported for individual plots (FHM National Technical Report; Conkling et al., in press). Management practices on sensitive soils should reflect the increased potential for physical disturbance through Best Management Practices. It is important to note that equipment limitation ratings reflect a range of soil properties that might limit equipment use and are not specific to compaction. For example, soils in mountainous regions

such as West Virginia may have severe equipment limitation ratings as a result of steep slopes rather than compactable soil textures.

Changes in soil bulk density are often used as an index for changes in soil productivity (Froelich and McNabb, 1984). In general, field studies have shown that roots grow well in soils with bulk densities of up to 1.4 g cm^{-3} and that root penetration begins to decline significantly at bulk densities above 1.7 g cm^{-3} (Sutton, 1991; Fisher and Binkley, 2000). Less than 6 percent of cores collected from the upper 10 cm on FIA/FHM plots in 2000-2001 had bulk density values greater than 1.5 g cm^{-3} , supporting the assessment based on the crew field measurements that compaction was not widespread on the FIA plots measured. Repeated measurements of bulk density on subsequent visits, combined with other information collected on FIA plots (texture, coarse fragment content, surface disturbance, forest floor cover) may strengthen analysis of this indicator in the future.

Interpretation of the ecological significance of this indicator is limited by the fact that there are no widely accepted standards of what constitutes “significant” compaction. Tree species differ in their tolerance to compaction and reduced soil aeration and evidence of surface compaction may not necessarily correspond to a measurable impact on stand productivity. For example, in some coarse-textured soils, compaction has been shown to have a neutral or even beneficial effect on productivity by increasing water holding capacity (e.g., Powers and Fiddler, 1997; Brais, 2001; Gomez et al, 2002). Compaction data from the FIA and FHM programs are intended to provide a “presence/absence” index of the occurrence of disturbed soils across the landscape. In order to determine the ecological significance of this disturbance, linkages to more

detailed process-level research into the relationship between soil disturbance and tree response are needed to determine both the severity of compaction necessary to cause significant reductions in site productivity as well as the level of reduction in site productivity that will be considered significant (Heninger et al., 2002).

D. LIMITATIONS TO THE DATA

Like other indicators within Criterion 4, soil physical properties are not conventionally monitored in a way that facilitates national reporting. Effects of management practices on soil physical properties are typically made on a site-specific basis. Compilation of data collected at the research scale is difficult because measurements of soil strength are sensitive to variations in soil moisture content, which complicates data comparison across different sampling dates or regions.

Soil sensitivity maps based on limitation ratings are useful in understanding coarse scale patterns related to soil physical properties. However, the Woodland Equipment Limitations Rating is an interpretive rating intended to describe only the potential limitations for using equipment. These maps do not reflect the actual status of the soil with regards to compaction or other physical disturbance. Furthermore, estimates of soil sensitivity are static products that reflect physical properties at the time of mapping. In addition, both the scale of the STATSGO soil data (1:250,000) and the use of weighted averages to define limitation ratings within an entire mapping unit preclude the use of this data at anything other than a national or regional scale. More detailed estimates should be based on the county-level State Survey Geographic Database (SSURGO) database at mapping scales ranging from 1:12,000 to 1:63,360.

An additional limitation with the soil survey limitation ratings as applied in this report is that the aggregation scheme averages the limitation ratings across both woodland and non-woodland components. Because equipment limitation ratings are not assigned to non-woodland soils, calculating a weighted average across the entire mapping unit will have the effect of reducing the overall limitation rating. As a result, a map unit that has been identified with a “slight” limitation rating may reflect either a high proportion of woodland soils at low risk for problems related to the use of equipment or a high fraction of non-woodland soils that were not rated. Details of this limitation are provided in Appendix A. This product should only be used to illustrate general trends across large areas and not for use in specific management applications.

The FIA/FHM soil indicator program is still in the implementation phase and plots have not yet been established in all states. As such, data analysis is necessarily limited in scope and is restricted only to those states for which plots have been measured. For states in which data collection has been implemented, current measurements of compaction are based primarily on visual estimates of compacted area. However, subsurface compaction more than a few years old may not be readily visible from the surface. In addition, no measurements are currently made regarding the degree or intensity of compaction. Pilot studies are currently underway to develop more quantitative measures of soil compaction based on the use of pocket penetrometers. The addition of bulk density measurements to the sampling protocols is expected to strengthen this analysis in the future. Effective use of bulk density data as an indicator for assessing temporal trends requires that the inherent variability within a given plot is low enough to be able to detect changes in bulk density over time. Additional research is needed to determine how variability in

soil density will be incorporated into these assessments and how this variability will be aggregated at multiple spatial scales.

Finally, even where reliable estimates for soil compaction are available, interpretation of the ecological significance of this soil disturbance is limited because tree species differ in their tolerance to compaction and reduced soil aeration. That is, the same level of compaction may have severe implications for one site but carry little significance for others. Soil texture and coarse fragment contents are primary factors to consider when determining the significance of soil compaction. Studies initiated as part of the USFS long term soil productivity program are yielding insights into the long-term effects of compaction and physical disturbance on processes within specific forest systems (e.g., Powers and Fiddler, 1997; Stone and Eliooff, 1998). These studies highlight the importance of interpreting soil compaction within the context of specific ecological systems. Further insight into the influence of soil physical properties on plant physiology may also be derived from calibration with important processes such as water infiltration, establishment of new tree seedlings, root growth, and stand growth for different soil types.

Soil data collected on FHM and FIA plots are intended to be interpreted as one part of a multi-tiered approach for detecting changes in soil properties across the landscape. FHM has five major activities: Detection Monitoring, Evaluation Monitoring, Intensive Site Monitoring, Research on Monitoring Techniques, and Analysis and Reporting (Tkacz, 2002). Detection Monitoring consists of nationally standardized aerial and ground surveys designed to collect baseline information on the current condition of forest ecosystems and to detect changes from

those baselines over time. Data presented in this report were collected as part of this effort. The ground survey portion of the detection monitoring program has since been transferred to FIA. Evaluation Monitoring studies examine the extent, severity, and probable causes of changes in forest health identified through the Detection Monitoring surveys. Intensive Site Monitoring projects are conducted to enhance understanding of cause and effect relationships and assess specific issues at multiple spatial scales. Research on Monitoring Techniques focuses on developing and refining indicator measurements to improve the efficiency and reliability of data collection and analysis at all levels of the program (Rogers et al, 2001). Finally, Analysis and Reporting activities are designed to synthesize information from various data sources both within and external to the USDA Forest Service to produce reports on status and change at national, regional, and state levels. As such, soil data reported in this analysis should be viewed as an initial assessment to detect changes in the presence of reported compaction. More detailed research collected under other portions of the FHM program is still needed to determine the extent and the ecological significance of these data.

E. IF CURRENT DATA ARE NOT ADEQUATE TO MEASURE THE INDICATOR, WHAT OPTIONS ARE AVAILABLE FOR REMEDY?

The FIA/FHM soil indicator represents the only nationally consistent, repeated measurement of compaction on forest soils. Since 2000, bulk density samples have been collected on all plots. Used in conjunction with information on soil texture, coarse fragment content, and total organic carbon content, these data will provide a direct measure of changes in the extent of compaction over time. In addition, pilot studies are underway to evaluate the use of a pocket penetrometer

on FIA plots to provide a more quantifiable index of soil compaction beyond the estimates currently collected. These pilot studies will also address the development of relative indices of compressibility to compensate for inter-plot differences in soil moisture content and bulk density at the time of measurement.

As with other soil indicators, additional research is needed to quantify the impact of physical disturbance on forest health and productivity. A mechanism for conducting this research already exists as part of the FHM Evaluation Monitoring and Intensive Site Monitoring programs. Where possible, additional process-level research should be used in combination with plot data to improve the scaling and interpretation of data from FIA/FHM plots. For example, the long term soil productivity research initiative (LTSP) was initiated by the Forest Service in 1989 to evaluate the effects of timber management practices on long-term soil productivity. By combining data on the changes in site productivity and compaction under different management practices with statistical information on forest management practices within regional ecological units, interpretations about the potential effects of compaction on forest health and plant physiology can be derived for different forest systems (e.g., Powers and Fiddler, 1997; Stone and Elioff, 1998). Additional insight into the impact of soil physical properties on plant physiology may also be derived from calibration with important processes such as water infiltration, establishment of new tree seedlings, root growth and stand growth for different soil types.

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APPENDIX A. STATSGO DATABASE STRUCTURE AND AGGREGATION PROCEDURE

The USDA National Resource Conservation Service leads the National Cooperative Soil Survey and is responsible for collecting, storing, maintaining, and distributing soil survey information for privately owned lands in the United States (USDA NRCS, 1994). The NRCS has established three soil geographic soil databases representing different sampling intensities and scales. The State Soil Geographic database (STATSGO) was designed primarily for resource planning and management at the regional, multistate, river basin, and multicounty levels. With the exception of Alaska, STATSGO provides national coverage of U.S. soils at a scale of 1:250,000; Alaskan soils are mapped at a scale of 1:2,000,000. Metadata for STATSGO data and compilation procedures can be obtained from the National Resource Conservation Service at http://www.ftw.nrcs.usda.gov/stat_data.html.

In county-level soil maps, each map unit usually represents a single soil component. In contrast, each map unit on a STATSGO map can contain up to 21 different components. Although attribute data is provided for each soil component, there is no visual distinction as to the location of these components within the mapping unit. For example, a mapping unit map may contain a 10% inclusion of a wetland soil type; however, there is no way to determine which 10% of the mapping unit this wetland type represents. In addition, each component consists of multiple layers representing different soil horizons. Development of interpretive maps requires aggregating data from the lowest level in the schema (layer) up to the component level and then aggregating component level data up to the map unit level.

Equipment limitation ratings within the STATSGO database are assigned as text (e.g., “severe,” “moderate”, “slight”). Interpretive maps were developed from these data by assigning a numerical value to these three rating scales. A weighted average of component data was then determined for each map unit by multiplying the mean value for a given soil component by the percent of the mapping unit represented by that component and then summing across all components as follows:

$$(1) \quad \text{Weighted Component Rating} = \text{Component limitation rating} * \text{Fraction of map unit in component}$$

$$(2) \quad \text{Map Unit Weighted Rating} = \sum \text{Weighted Component Ratings}$$

The weighted limitation rating for the map unit was then used to classify the map unit into one of three limitation ratings following the nomenclature used by the NRCS: “slight,” “moderate,” and “severe.”

Map units may contain both woodland and non-woodland components. However, limitation ratings are assigned only to woodland components. When weighted averages are taken over a map unit that contains both woodland and non-woodland components, the numerical limitation rating is reduced in proportion to the size of the non-woodland component. As a result, the limitation ratings in Figure 22.1 reflect both the limitation ratings as well as the fraction of the plot that is defined as a woodland soil. Map units that have been identified with a “slight” limitation rating may represent either a high proportion of woodland soils at low risk for physical

disturbance related to the use of equipment or a high fraction of non-woodland soils that were not rated. This mapped product should only be used to illustrate general trends across large areas and not for use in specific management applications.

FIGURE CAPTIONS

Figure 22.1 Equipment limitation ratings derived from the STATSGO database. Equipment limitation ratings for each soil component were converted to a numerical scale and a weighted average determined for each map unit (see Appendix A for details of aggregation scheme). The final rating for each map unit reflects both the limitation ratings assigned for woodland components within a map unit as well as the fraction of the map unit that contains woodland soils.

Figure 22.2 Mean compacted area reported on FHM plots (1999-2000). Symbols represent the mean value of four measurements made on each plot. The size of the symbol indicates the percent of the plot reporting evidence of surface compaction. Mean plot values were then aggregated by Bailey's ecoregion and the mean value of each ecosystem used for classification. Differences in shading are not intended to represent statistical significance. Portions of ecoregion sections falling in states for which no data were collected have been removed from this analysis.

Figure 22.3 Frequency distribution of percent compacted area reported on FHM plots (1999-2000).

Figure 22.4 Frequency distribution of bulk density values collected from 0-10 cm cores on FIA/FHM plots (2000-2001).

Figure 22.5 Bulk density as a function of organic carbon content for 0-10 cm soil cores collected on FIA/FHM plots in 2000 and 2001.

