Soil Compaction: Causes, Effects, Management in Bareroot Nurseries[1]

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Abstract - Although soil compaction appears as a simple reduction in soil volume, the effects on the soil are far more complex and influence many processes. Perhaps the most significant impact of compaction is the change in soil water relations which in turn, has many impacts on plant root growth and health. This article describes compaction and how to locate and measure it in bareroot nurseries. Because organic residues can significantly reduce compaction and its effects especially in a long term soil management program, the mechanisms of residue effects on compaction are discussed. Guidelines for preventing and/or managing soil compaction in nurseries are also presented.

INTRODUCTION AND OVERVIEW

Soil compaction is associated with nearly all field operations (wheel traffic, tillage with various implements, undercutting, and lifting) in bareroot nurseries. Operations conducted under wet soil conditions, in particular, favor compaction and soil structural damage. Establishment and use of permanent tractor paths in nurseries reduces the compactive effect of wheel traffic, but other nursery operations must also be scrutinized carefully for production of compacted soil layers.

Soil compaction can be beneficial or adverse depending on its severity and location in the nursery beds. Evidence of detrimental compaction can be elusive, but may be suspected in bareroot nurseries when water ponds on the surface, seedling vigor is poor, and root diseases are abnormally severe or appear to increase (Duryea and Landis, 1984).

Compaction is defined as the rearrangement of aggregates and primary particles into a state of higher bulk density-and lower porosity when a load (or stress) is applied to a soil (Warkentin,1984; Bradford and Gupta, 1986). The first impact of compaction is the loss of pore space between aggregates (interaggregate pore space) as the soil volume is decreased (Cruse and Gupta, 1991). Smearing or crushing of individual aggregates (intra-aggregate pore space) occurs in the next stage as the soil volume is reduced more. The loss of interaggregate pore space has a major effect on water infiltration and drainage, gas exchange and aeration (oxygen diffusion), mechanical resistance to root penetration and proliferation, heat movement, and biological activity of both soilborne pathogens and the host organism (fig. 1; Allmaras et al., 1988a). When individual aggregates are crushed only the smallest pores remain and the biological environment deteriorates even more.

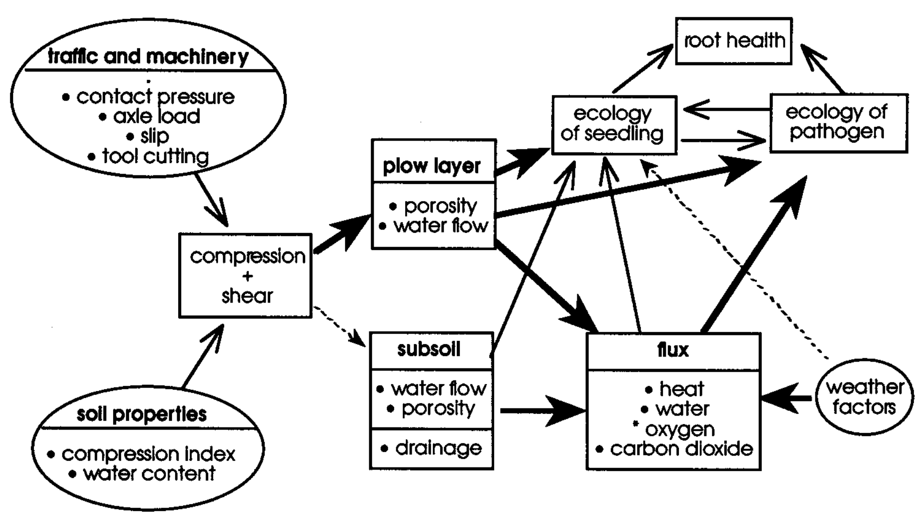

Figure 1. Relationships between soil compaction and root health; a diagrammatic guide.

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Once aggregates breakdown and only very small pores dominate, regeneration of favorable structural conditions may take years (Hakansson et al., 1988). The extent and severity of compaction are therefore important considerations due to their effects on physical, biological, and hydrological processes.

An alternative explanation for compaction is that the rearrangement of aggregates and primary particles changes the total pore space, pore size, pore continuity, and soil strength because of the solid-to-solid contact (Gupta et al.,1989). These changes of soil properties can then be used to predict a response of processes like water flow, aeration status, heat flow, and mechanical resistance to rooting.

The above definition of compaction involved the action of an applied load or stress. The change induced in the soil is considered as a strain. Soil mechanics specialists then consider axle load, contact pressures, wheel slip, and tool cutting or sliding as stress factors —compression and shear are the major modes of strain (fig. 1).

Along with observations on seedling growth and soil drainage, soil measurements and a log of field operations are needed to discover compacted areas and layers, their cause, and to take remedial action. Field management to reduce or minimize soil compaction can be linked somewhat to general knowledge about stresses imposed by traffic, tillage machinery, and other operational equipment/practices. Soil water content at the time of field operations ranks high in importance along with axle load, contact pressure, and slip as factors that contribute to adverse compaction. Organic matter management and additions are used for many purposes in bareroot nurseries (Davey, 1984), but nursery managers should examine more closely the influences of organic residues and organic matter on soil structure, reduction of compaction, and associated effects on soil drainage and aeration.

The objectives of this paper are to discuss the effects of compaction, where and how to locate and measure compaction in the nursery field, the interaction between organic matter and compaction, soil ecological considerations, and implications for soil management in bareroot nurseries.

PROBLEMS

Problems induced by excessive compaction are runoff, soil erosion, slow infiltration and soil crusting, impaired or delayed internal drainage, decreased soil water storage, shallow and sparse plant rooting, reduced nutrient and water uptake, accelerated denitrification, production of toxic materials due to soil reducing conditions, fewer field days, and more root disease from pathogens such as *Pythium, Phytophtora, Aphanomyces, Fusarium* and *Rhizoctonia* spp. Most of these problems are linked to adverse water relations caused by retarded infiltration, less air-filled pore space, and impeded water movement. Many of these problems are discussed in review articles, for example: a) root-system centered response to soil compaction (Taylor and Brar, 1991; Voorhees, 1992), b) gaseous flux and aeration responses to soil compaction (Allmaras et al., 1988a; Smucker and Erickson, 1989), c) oxygen relations in root environment (Drew, 1983), and d) mechanically impeded root growth (Bathke et al.,1992).

BENEFITS

There are instances where moderate, deliberate compaction of soil is beneficial. Seed-soil contact (Hadas, 1982) is routinely improved by packing soil around the seed. This contact is necessary to transmit water to the seed for germination. Ideally, such compaction should occur so that the soil immediately below the seed has a higher strength than the soil above the seed. A moderate amount of compaction in the plow (Ap) layer prompts some agronomic crops, such as peas and soybeans to develop more fibrous root systems that are less dominated by a tap root (Voorhees et al.,1975; Russell, 1977; Smucker, 1993). However, excessive compaction results in a more branched root system where the primary axis roots do not respond by growing downward according to geotropic response. Moderate compaction may also encourage clod formation in formerly compacted zones such as old wheel tracks (Voorhees et al.,1978). Tillage actions which form these types of clods also serve to incorporate crop residue into them (Staricka et al.,1992). A moderately compacted soil with a surface mulch is considered best for reducing evaporation in seedbeds (Hadas,1982) and during summer fallow (Pikul et al.,1985), and when field traffic is controlled, compaction of traffic paths results in improved vehicle traction (Swan et al., 1987).

LOCATING AND MEASURING COMPACTION IN THE FIELD

Several methods are available for locating and measuring soil compaction. These include methods which can be used in the field to measure compaction after it has occurred as well as laboratory tests that evaluate soil responses to dynamic or static loading.

Field Methods

Field methods most frequently used to assess soil compaction involve measuring soil bulk density or soil resistance to penetration.

Soil bulk density is the dry weight of soil that occupies a known volume of solids plus water plus air. It is expressed as grams of oven-dry soil per cubic centimeter (g/cm^3). Within a given soil, bulk density is a measure of how closely soil particles are packed, so that relatively higher bulk densities are an indication that compaction has taken place. However, differences in bulk density between different soil types cannot be directly related to compaction effects because pores may have different sizes or different connectivity.

Various methods of measuring soil bulk density, including coring, excavation, clod density, and gamma radiation have been reviewed (Blake and Hartge, 1986). Improvements in the coring method (Allmaras et al., 1988b; Doran and Mielke, 1984) facilitate locating and measuring thin, compacted layers common in tilled fields. An especially simple and useful modification of the excavation technique is the compliant cavity (Bradford and Grossman, 1982). The clod density method may be helpful in evaluating the effect of historical practices on clod or aggregate density. These effects may be negative (excessive compaction or fragmentation) or positive (use of manure or other organic amendments).

Cone penetrometers are commonly forced through the soil to measure soil penetration resistance (Bradford, 1986). Penetration resistance is a pressure (a vertical force divided by the basal area of the cone) expressed in units of megapascals (MPa). Cone shape and rate of advance into the soil must be specified. The most popular penetrometer is the "Corps of Engineers" specification with a cone basal area ranging from 1.3 to 3.2 cm^2, a driving shaft 46 cm long with extensions, and a cone with a 30° included angle (Bradford, 1986). Penetration resistance represents the combined effect of cohesive and frictional characteristics of the soil. Therefore, soil water content and soil type, as well as soil density, affect soil penetration resistance. This means that differences in soil penetration resistance between either different soil types or the same soils at different water contents must be adjusted to measure compaction effects. For this reason penetrometer measurements should have associated soil water measurements. The ease and rapidity with which penetration tests can be made permits many of these measurements to be taken within the area of interest.

Two criteria have been suggested to determine whether compaction is significantly affecting root growth rate, and another criteria has been suggested to determine if compaction is significantly affecting soil structure (Gupta and Larson, 1982). The first two criteria, 1) an excess of 2 MPa resistance to soil penetration as determined by a cone penetrometer, and 2) less than 10 percent air-filled pore space, can be combined to estimate the effects of anaerobic conditions and mechanical impedance on root growth rate. The other criterion is the combination of applied stress and soil water content needed to begin the consolidation of soil aggregates after the interaggregate pore space has been removed by increasing compactive stress.

Neither bulk density nor soil penetration resistance provide any information about the geometric arrangement of soil particles or pore-size distribution. However, soil structure and porosity are critical properties influencing air and water flow in soil, and must often be measured directly to determine how soil layers of different densities or penetration resistance affect these properties.

The following examples show field compaction and illustrate the variety of methods that can be used for description. A hand-held cone penetrometer was used to measure compaction profiles (fig. 2) in a clay loam subjected to four different types of primary tillage for 10 years (Swan et al.,1987). Resistance was measured con-

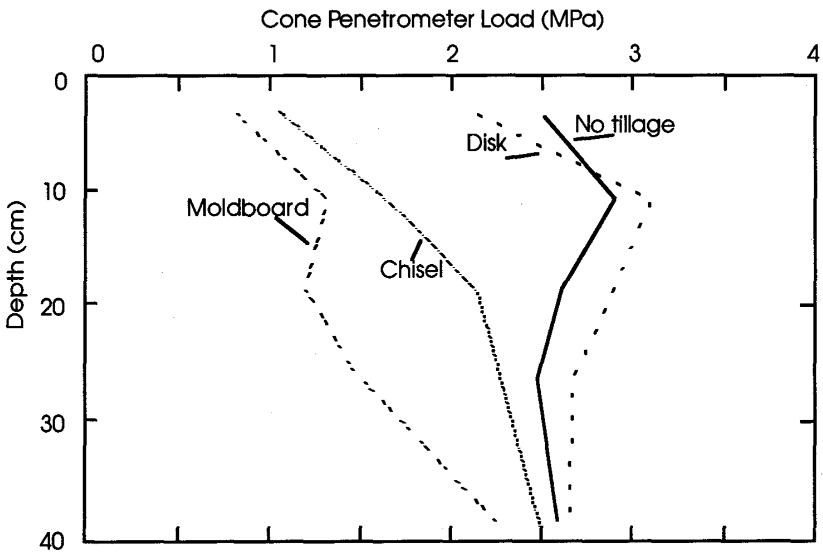

Figure 2. Soil compaction produced by primary tillage tools in a long-term tillage system and measured with a cone penetrometer (after Swan et al., 1987).

tinuously as the penetrometer was forced through the soil to a depth of 38 cm. Soil resistance in the moldboard plow treatment approached 2 MPa (which is considered a critical load for rooting) at about 28 cm, or the plane between the Ap layer and the untilled subsoil. The continuous disk treatment showed a disk pan at 10 cm, the common depth of penetration for a disk. The no-tillage and disk treatments had about the same resistance profile, except that the no-tillage treatment did not have the disk pan and had not been disturbed in the 2 to 6 cm depth range. Both the moldboard and chisel treatments had less compaction than the other two treatments. The moderately compacted zone at 10 cm in the moldboard treatment may have been caused by surface traffic, but the resistance profile did not identify a plow pan usually found at 25 to 30 cm in this soil (Logsdon et al.,1990). Resistance profiles for the chisel, no-tillage, and disk treatment should all be alike in the depth range of 15 to 38 cm. The differences between these treatments may have been due to different soil water contents (Bradford, 1986) which where not measured; as was mentioned earlier, cone penetrometer loads can be misleading unless soil water profiles are measured to make a correction. Some researchers avoid the problem of variable soil water content by making measurements in wet soil using a more sensitive cone penetrometer (Bradford, 1986).

Bulk density profiles in fig. 3 illustrate individual and interacting effects of axle load and soil water content on soil compaction - both severity and depth of compaction. An axle load of 4.5 ton is normal for medium sized tractors; a partially loaded combine has a 9-ton axle load; and a large grain wagon fully loaded may have an 18-ton axle load. In the "dry" regime soil water content in the upper 20 cm was in the range where compaction

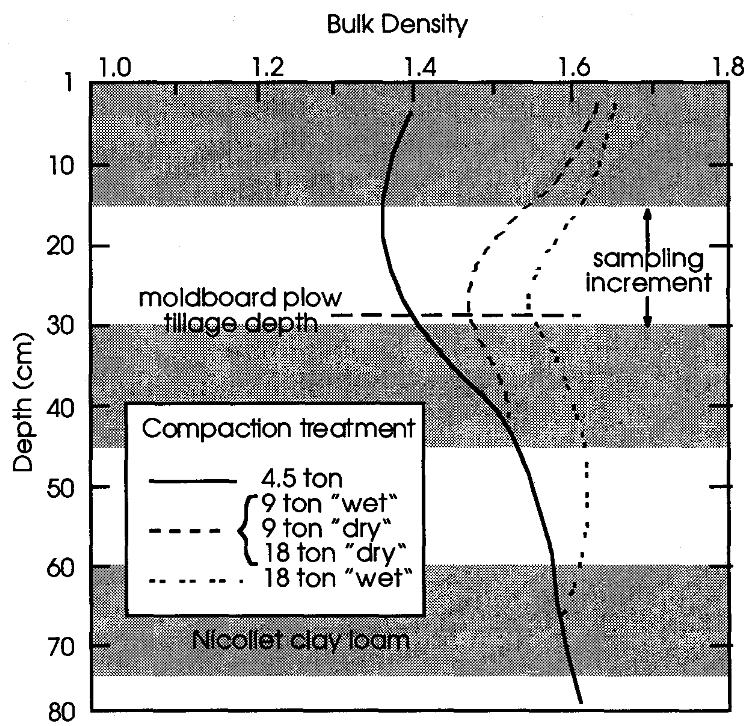

Figure 3. Compaction produced by different axle loads applied where the soil water regime was "wet" or "dry" (after Voorhees et al., 1986).

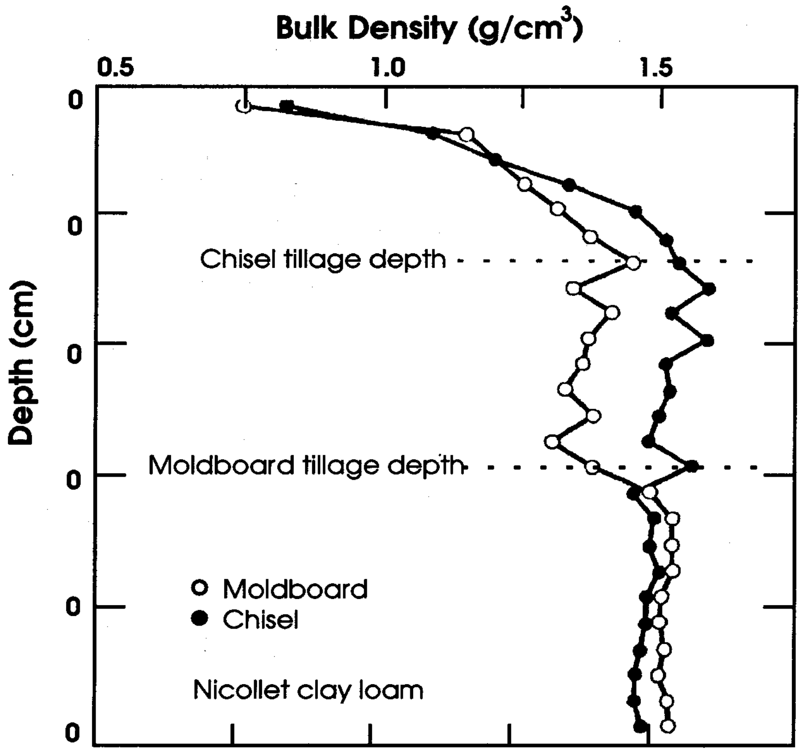

Figure 4. Changes in bulk density characteristic of moldboard compared to chisel plowing (after Staricka et al., 1990).

would be severe, and the rest of the profile was near the water content at permanent wilting where resistance to strain is a maximum. In the "wet" regime the whole 80-cm profile was wetter than the water content expected for most severe compaction. One bulk density profile explained compaction from the 9-ton axle load for both soil-water regimes and the 18-ton axle load on the "dry" regime. The maximum depth of compaction was about 30 to 40 cm. An additional increment of compaction was produced by the 18-ton axle load on the "wet" soil – this compaction extended to nearly 60 cm. The lower bulk density at 25 to 40 cm is characteristic in the tilled Nicollet clay loam because frequent soil rupture by tillage has rendered the soil in the Ap layer more susceptible to compaction, and overburden from historic glaciation has compacted the subsoil.

Bulk density profiles in fig. 4 compare the influence of primary tillage, after the same secondary tillage had penetrated no deeper than 10 cm. Soil cores were purposely not taken where there was traffic during secondary tillage. Moldboard plowing produced a lower bulk density than chisel plowing in the Ap layer extending from 6 to 30 cm. The marked increase in bulk density of the moldboard treatment at 30 cm is a characteristic that defines the depth of penetration while chiseling only shows a marked decrease of bulk density above its depth of penetration. Moldboard plowing often shows a plow pan near the maximum penetration depth, and can be either from the current tillage or a residual from operations of a previous year (Logsdon et al., 1990).

Figures 3 and 4 also illustrate bulk density profiles obtained by two different methods of core sampling. Bulk density profiles in figure 3 were obtained using a tractor-mounted hydraulic coring device (nominal core diameter of 4.8 cm and length of 15 cm). Profiles in figure 4 were obtained using a hand sampler (core of 18 mm diameter and 20 mm long). Each profile in figure 3 is a composite type average of 8 cores – those in figure 4 were obtained from 15 cores. The smaller cores and the 2-cm increment of depth used to develop the profiles in figure 4 nearly always detect depth of tillage and associated tillage pans even when they are no thicker than 4 cm, and these thin tillage pans can impede water movement (Allmaras et al., 1988a). In contrast, the larger cores used to develop the profiles in figure 3 rarely distinguish tillage pans produced by either traffic or tillage tools.

Laboratory Methods

Several laboratory procedures can be used to evaluate how factors such as machinery loading, soil water content, and soil physical properties can be varied to control compaction. The Proctor test (ASTM, 1979) uses dynamic soil loading to measure the maximum soil density produced per unit of energy applied. This method is most useful for engineering applications of soil mechanics. The dynamic loading and unloading in a fraction of a

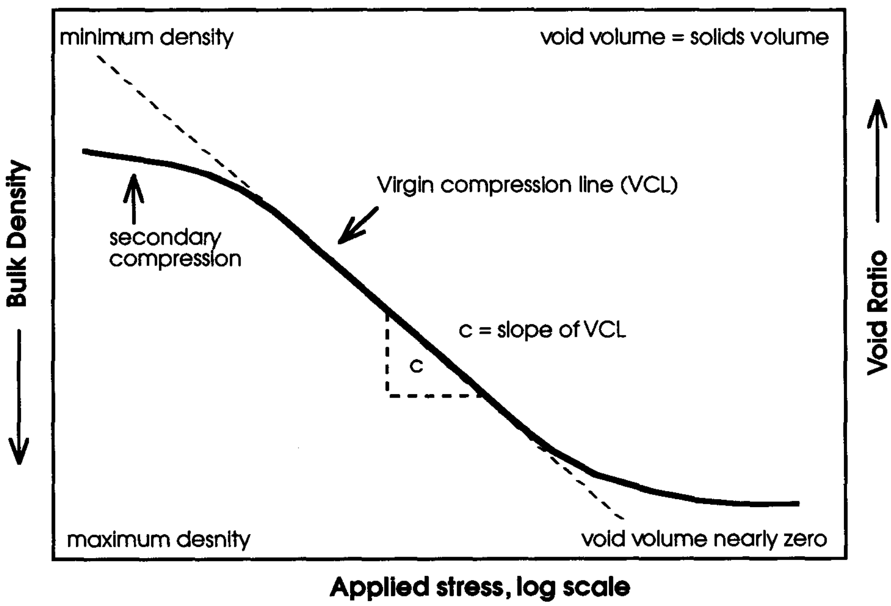

Figure 5. Diagrammatic description of the soil bulk density or void ratio response to uniaxial stress (the solid line traces the compression response; the dashed line helps define the virgin compression line; the secondary compression curve and where it meets the virgin compression line depends on historical stress applied).

second in the Proctor test appears similar to that occurring during the passage of a wheel, but the method has not proven useful in analyzing and interpreting traction traffic (Hadas et al.,1988). Soil response to static loading can be measured in a consolidometer or triaxial cell, or merely a uniaxial stress applied to a soil in a confined container (Bradford and Gupta, 1986). The loading rate is so slow that it may be considered static. These static toad tests are used to derive the compression index, which is identified in figure 1 and defined as the change in bulk density per unit of applied uniaxial stress along the virgin compression line (see fig. 5). These laboratory tests can be used to predict the depth of soil strain due to such factors as tire width and axle load (Swan et al.,1987). However, predictions from these tests (Warkentin, 1984) are based upon homogeneous soil and often fail when there are distinct soil layers. The compression index of figure 5 is sensitive to density of aggregates, clay content, and organic matter content; the density of aggregates changes the secondary compression line. When water content is changed the compression index does not change but the virgin compression line translates down (to a larger bulk density) as the water content is increased (Gupta and Larson, 1982).

Strain Gauge Studies

Measurements of bulk density or load on a penetrometer cone used after compaction has occurred in the field can detect traffic compaction, depth of tillage tool penetration, and a tillage tool pan, but are less sensitive in detecting the maximum depth of traffic induced compaction. Strain gauges are now being used in field studies to directly measure strain at various depths under various configurations of axle load, contact pressure, rutting, ground speed, and wheels or tracks (Kinney et al., 1992) because they record the displacement as it happens.

Strain curves in figures 6 and 7 show the results of two such tests. Strain gauges 140 mm long were

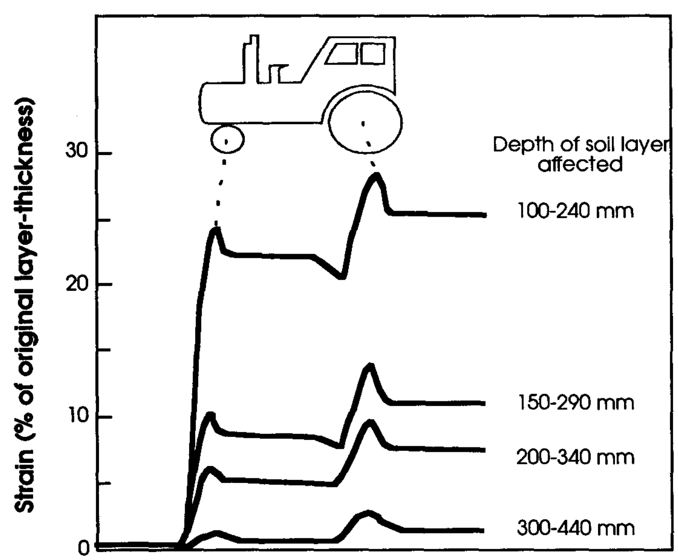

Figure 6. Strain produced by a medium-sized, rubber-tired tractor (without drawbar load) during travel on the soil surface (after Kinney et al., 1992).

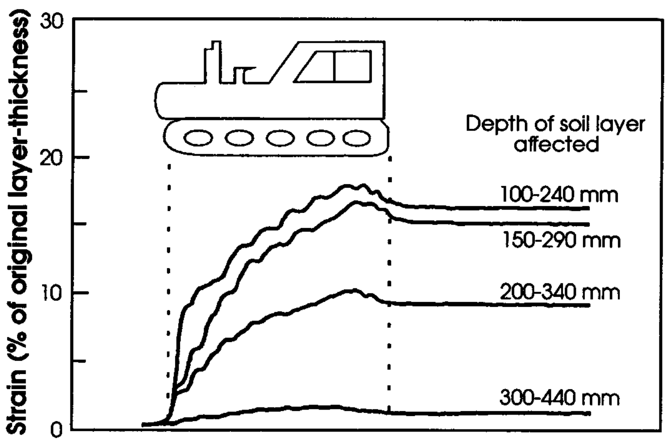

Figure 7. Strain produced by a crawler tractor (without drawbar load) during travel on the soil surface (after Kinney et al., 1992).

placed in the soil so that the top of a gauge was 100,150, 200, and 300 mm below the soil surface, and the bottom of the gauge was anchored at 240, 290, 340, and 440 mm, respectively, below the surface. Strain was measured by the movement of the top of the gauge as a front and rear tractor tire (fig 6) or a track (fig. 7) passed over the gauge. A strain of 25 percent represents a 35 mm reduction in length of the soil layer between the upper and lower bounds of the strain gauge. An elastic rebound of the soil occurred after the passage of both the front and rear tire (or of a track), but the strain curves also verify that traction traffic can produce permanent strain below the level of the plow pan – an old plow pan was noted in this study at 300 mm. These levels of strain are conservative in that the tractors were not drawbar loaded. Strain curves in figures 6 and 7 clearly verify that a wheel tractor produces more compaction at shallow (100 to 240 mm) depths because of contact pressure, and that strain at 300 to 440 mm is nearly the same for both traction devices because the axle load is about the same even though the contact pressures are greatly different (Kinney et al., 1992).

Guidelines for Field Diagnosis

Cone penetrometers can be used for a preliminary survey to locate suspected compacted areas and layers. Areas of a nursery where problems such as poor drainage, poor seedling performance, or disease have been noted should definitely be examined for compacted layers. As was discussed in figure 2, a continuous record of load on the penetrometer cone must be made beyond the depth where no compaction is expected. Bradford (1986) suggests an initial 50 to 60 cm horizontal spacing of penetrations with a later fill-in should large differences be experienced between successive penetrations. He also describes two types of penetromters, the "Corps of Engineers" type for vertical penetrations and a pocket penetrometer for examining compacted layers by horizontal penetrations along the vertical wall of a soil pit. One cannot over emphasize the need to carefully log prior field operations with some estimate of the paths made by tractors and equipment – this should be done before extensive penetrometer use. When compacted layers are confirmed, bulk density cores can be used to develop a more accurate assessment of the depth, thickness, and density of these layers. As was pointed out earlier, smaller cores are more accurate in locating and characterizing thin compacted layers common in cultivated areas. At least 18 cores should be taken through the profile to at least 15 cm past the deepest suspected compaction (see fig. 4). When horizontal variation in the compacted layer(s) is suspected a set of soil cores is needed for each vertical variation. Further assessment of these compacted layers, such as porosity measurements, may be required to determine if they are adversely affecting rooting and movements of water and air.

ORGANIC MATTER – SOIL COMPACTION INTERACTIONS

Significance

Organic matter maintenance is a primary concern for continued seedling production in bareroot nurseries (Davey, 1984). Eighty-six percent of managers of bareroot nurseries surveyed for the *Forest Nursery Manual* (Duryea and Landis, 1984; Davey, 1984) were concerned that organic matter levels were too low. Of the five most serious problems identified by the managers, compaction and organic matter maintenance each were included in 62 percent of the lists (Warkentin,1984); inadequate drainage was included in 43 percent of the lists.

There were frequent comments about the need for more organic matter to control compaction and improve drainage. The relationship among these three concerns has not received the attention that it deserves. There are many observations of soil organic matter content changes in response to organic additions in the agronomic and bareroot nursery literature, but relationships between additions of soil organic matter and the resistance of amended soil to compactive forces are difficult to analyze and apply to soil management plans. There is a need for a systematic and theoretical approach to organic matter interactions with soil structure. Because organic matter also serves as a food reserve for biological activity there can be long-term soil structural changes.

Mechanisms

Soane (1990) reviewed organic matter interactions with compaction of soils especially in agronomic situations, although he recognized that horticultural enterprises are naturally concerned because of their larger additions of organic materials. There are six mechanisms by which organic matter may influence the compression and compactability of soil (Soane, 1990):1) bonding forces between particles mostly within aggregates, 2) elasticity associated with organic materials lodged among aggregates, 3) dilution effect caused by the lower bulk and particle density of organic materials compared to mineral soil, 4) fungal and root filaments to bind aggregates together, 5) electrical charge effects on clays, and 6) surface coating to change friction between aggregates.

Effects

The effect of organic matter on the tolerance of aggregate structure to compaction is typified by a study (O'Sullivan, 1992) where previous cultural practices had resulted in a one percent increase in soil organic matter (long-term avoidance of moldboard plowing) in one area compared to another area (subjected to continuous moldboard plowing) of the same soil types. As more stress or load was applied (as in fig. 5), soils with higher organic matter had lesser decreases in specific volume (ratio of total to solid volume) and lesser increases in dry strength (resistance to crushing forces) compared to soils with lower organic matter. This relationship held over a range of soil moisture contents. Both soils showed greater specific volume decreases and dry strength increases under a given load or stress as soil moisture increased; however, soils with higher organic matter contents were more tolerant of compaction because of resultant changes in soil aggregate structure that reduced the dry strength and specific volume responses to applied stress.

Some other ways to evaluate compaction effects on intra-aggregate structure depend on the increase of cohesion upon drying, at which point individual aggregates are crushed to measure their tensile strength (Boyd et al.,1983; Dexter and Kroesbergen,1985). Bonding forces inside individual aggregates can also be studied when wet (Kemper and Rosenau, 1986).

Before organic residues undergo extensive decomposition they can reduce compaction due to elasticity or rebound. Rebound is measured as a relaxation ratio (fig. 8), which is the bulk density of the test material under a stress divided by the bulk density after the stress is removed. When crop residues or organic additions are incorporated into soil, nearly all of the material is clustered and packed between aggregates (Staricka et al. 1991), where relaxation effects can preclude or mitigate compaction. Undecayed and partially decayed straw both have a relaxation ratio much larger than non-amended soil, especially at an applied stress of

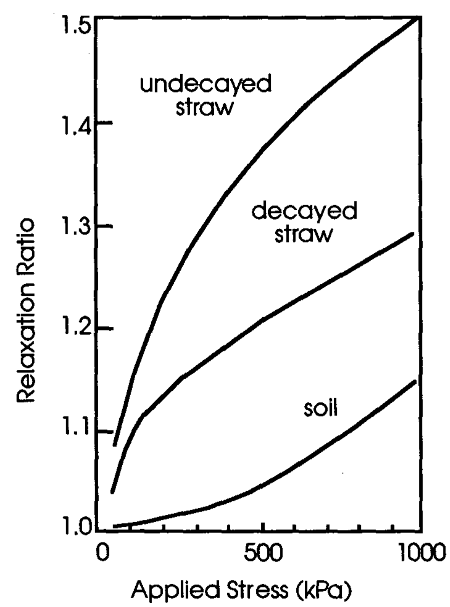

Figure 8. Relaxation ratio (elasticity) of soil compared to undecayed and decayed wheat straw (after Guerif, 1979).

300 kPa or less (fig. 8). Stresses applied in the field are usually in the 100 to 200 kPa range. This effect does not show up in the compression index as determined in figure 5, but instead the virgin compression line translates to a lower bulk density when organic additions are made (Guerif,1979; Gupta et al.,1987).

The lodging of long-chain molecules produced by decomposition of organic matter stabilizes soil aggregates and, therefore, maintains good soil structure. Interestingly, the rupture and compressive forces associated with tillage actions are one means by which residue, as it decomposes into long-chain molecules, are lodged inside aggregates (Dexter, 1988; Staricka et al., 1992). Plant rooting can also place these molecules inside aggregates (Oades,1993).

Incorporation of residues also leads to lower bulk density and greater water retention of soil, because organic materials have a lower particle density than soil materials. Organic materials are often clustered, whereupon their lower bulk density causes bulking of the soil. Soil volumes as small as 5 cm^3 had a lower bulk density as the weight of oats residue was increased in the soil volume (Staricka et al., 1991). This bulk density change was more than expected when taking into account the different particle densities of the oat straw and the soil, thus, a looser packing of the organic materials. Because cereal straws retain more water per unit mass at a given suction, water retention of soil with added straw was greater than with soil alone on a unit mass basis (Myrold et al.,1981).

SOIL ECOLOGICAL IMPLICATIONS

Compaction Effects on Root Function and Stress

Overall development of seedling roots may be influenced significantly by soil strength and compaction, soil temperature, and toxic concentrations of aluminum, salts, pesticides, and plant toxin (Russell, 1977; Asady et al.,1985). Seldom is the soil environment optimal for root growth under field conditions; stresses may result from water excess or deficiency, oxygen deficiency, mechanical resistance to root growth, sub or supra-optimal soil temperature, nutrient deficiency or imbalance, and pathogen or insect damage. Soil compaction can aggravate the effects of each of these potential abiotic and biotic stresses.

Compaction Effects on Root Pathogens and Disease Development

Interactions between a seedling root and soilborne pathogens are seldom predictable based upon each organism's separate response to aeration, penetration, and moisture stress. All of these stresses interact directly or indirectly with compaction. Such an interaction was documented (Miller and Burke, 1975) in a special root chamber in which bean roots were grown in a soil layered to simulate a compacted plowpan; soil water potential was held at -20 kPa (or -0.2 bars). In fumigated soil a 3-day treatment with reduced oxygen had little effect on plant growth 4 weeks later, but in soil infested with a root pathogen *(Fusarium* f.sp. *phaseoli)* there were permanent reductions in subsequent shoot and root growth. These responses intensified as the oxygen level was reduced (i.e. poorer aeration) during treatment. The ability of roots to penetrate the compacted layer was reduced by the *Fusarium* and essentially eliminated with the combination of low oxygen and the pathogen.

Compaction from both tillage implements and traffic can influence the survival and distribution of pathogen inoculum in soil. A plowpan was found at 20 cm depth in both wheat and pea fields (Kraft and Allmaras, 1985). These compacted pans were earlier shown to influence the severity and extent of pea root disease caused by *Pythium ultimum* and *Fusarium solani* f.sp. *pisi*. *Pythium* was characteristically found in the upper 20 cm of soil and was absent below the plow layer. The excessively wet plow layer in winter and spring favored *Pythium ultimum* in both its saprophytic and pathogenic modes. The *Fusarium* propagules were found throughout the upper 60 cm of soil, but their frequency was always low in the tillage pan just under the plow layer. The sparsity of fungus propagules in the tillage pan and their presence below it are related to the impaired drainage from compaction in the compacted layer and the saprophytic survival of *Fusarium solani* under dry soil conditions. However, in fields not cropped to peas for over 5 years, *Fusarium* was not detected in the plow layer, but was always recovered below it. Thus, the environmental optima for long-term survival of the *Fusarium* pathogen occurred in the relatively dry subsoil.

Excessive soil compaction affects the rate and distribution of root growth, and thus affects the chances of successful host-pathogen contact and the dynamics of root-pathogen interactions. For example poor aeration or axial constraints on root development (such as mechanical resistance) may reduce the rate of root tip advance by as much as 75 percent and may also induce formation of laterals much closer to the root tip. The result is a more compacted and stressed root system. Exudates produced by elongating and/or stressed roots stimulate dormant fungal pathogen structures (e.g. chlamydospores, microsclerotia) to germinate and grow. The overall result is that soilborne pathogens in compacted soils are more likely to intercept young lateral root and obtain sufficient nutrients to infect that root. This may not be as important a factor in *Fusarium* root diseases, however, because *Fusarium* spp. usually exist largely as colonies growing epiphytically on the root surface.

MANAGEMENT IMPLICATIONS AND GUIDELINES

While soil compaction is a simple operation, i.e., a reduction in volume of a given mass of soil, it is a complex and involved process that challenges both the best nursery managers and the most capable agricultural scientists. Soil compaction involves interrelationships between most of the physical, chemical, and biological properties of soil as well as environmental factors such as climate, weather, tillage and agronomic treatments, and crop use. In turn, the state of compaction of the soil is largely responsible for soil water, air and temperature conditions and subsequently affects seed germination, seedling emergence, root growth, pathogen problems, and most other phases of seedling growth and production.

Knowledge of the processes by which the state of compaction may be modified and controlled, as well as a means of measuring soil compaction, is therefore essential for effective, sustainable nursery production. The selection and management of tillage equipment and cropping systems in nurseries should be directed at producing the optimum state of compaction at appropriate depths in the soil for the crop production cycle. The following guidelines are suggested as a basis for assessing soil compaction and developing practices to prevent or ameliorate soil compaction, and should be considered when developing nursery soil management plans (see Boyer, 1993, for an example of a nursery soil management plan.)

Locating and Mapping Soil Compaction

A systematic survey of the nursery for compacted soil layers is an essential first step in dealing with compaction problems. Ideally, this would be included as a part of an intensive soil survey to develop an accurate soil map during the establishment of new nursery fields. The fields should be checked to determine the depth and intensity (bulk density) of compaction layers formed by equipment traffic during grading and leveling operations (Thompson, 1984). However, even where these operations were not done, prior land use may have formed serious compaction layers, or naturally formed impeding layers may be present in the root zone due to the erosion of surface layers. Some soils also have naturally formed clay pans or duripans. The presence of these natural pans can often be inferred from soil survey maps, but county soil survey maps are not accurate enough to delineate soil boundaries or pan depth and intensity in nurseries. A soil survey on a 100- to 200- foot square grid to accurately establish soil boundaries is recommended.

As mentioned earlier, areas with poor drainage, poor seedling performance, or repeated disease problems should be examined in production fields for soil compaction. A cone penetrometer can be used to initially determine the extent or area of a pan already suspected. However, care must be taken to insure that differences in soil water contents do not confound soil penetration resistance measurements. For an initial assessment, a series of vertical penetrometer measurements taken in the interior of the beds (not on the tractor paths) consisting of one reading every 2 to 4 feet (depending on the size of the area being surveyed) should suffice. These measurements should extend beyond the suspected area of the pan in order to obtain a comparison with unaffected soil. An alternative using a pocket penetrometer involves excavating a series of soil pits across the same area range and taking readings along the exposes soil face. Care must be taken to identify soil type boundaries in making these measurements, since different soil types will have different soil penetration resistance properties. Also, penetrometers may not always detect thin compacted layers that can impede air and water movement. For that reason, bulk density core samplings should be considered even when no compacted layers are detected with a penetrometer. Smaller cores are more effective in locating thin compacted layers, but are much more time-consuming than penetrometer measurements. Sampling recommendations for bulk density cores were discussed previously.

Ameliorating Initial Compaction Problems

If a natural or induced pan is detected during the initial survey, subsoiling should be done and no subsequent traffic should occur on the soil prior to preplanting tillage. However, this subsoiling should only be done in situations where the subsoil does not have good macroporosity (Taylor and Brar,1991; Voorhees, 1992). Soil surveys and soil taxonomic descriptions should indicate when there is macroporosity due to bioactivity and soil cracks. Whenever possible, controlled traffic lanes should be used for this operation. Permanent tractor paths (as discussed below) could be located at the time of this operation if possible.

Reducing and Ameliorating Compaction Due To Nursery Operations

Moldboard plowing and rototilling are likely to form tillage pans. These operations should be carried out so that only surface traffic occurs, i.e., tractor wheels should not travel in the furrow when moldboard plowing. This will avoid excessive compaction below the tillage layer. Bulk density measurements within the rooting zone (see fig. 3 and 4) are useful to assure that no compacted layers remain after subsoiling.

Rototilling also causes fragmentation of soil aggregates; aggregates with good internal strength are a means to prevent soil compaction and related problems of poor soil drainage. Adjust travel and rotation speed of rotary tillers so that beds are not overtilled – finely pulverized soil is only needed in the layer (or better yet the zone) where seeds will be sown.

As discussed earlier, soil organic matter content is an important factor in the ability of soil to resist compaction. Maintaining soil organic matter through green manure crops or direct application of material such as peat or sawdust (maybe both when possible) is therefore important for improving both chemical and physical soil properties.

Whenever possible, incorporate crop residue or organic material by shallow disking or rototilling followed by a chisel operation. Disks and rototillers are very efficient in incorporating residue, but leave a tillage pan that is likely to limit internal water drainage. Shank mounted tools such as chisel plows can help eliminate shallow tillage pans, but are not efficient residue incorporation tools. Tillage tools should be kept sharp and properly set for maximum performance. Dull, or improperly adjusted tools cause undue compaction.

Tractor paths should be relocated as accurately as possible in each production cycle. Compaction from repeated wheel traffic often extends below tillage depth (see chisel tillage in fig. 4), and can be difficult to ameliorate even with subsoiling. Compaction at this depth can impede water flow, perch water tables, reduce aeration even upward into the Ap layer. Moreover, compacted soil in traffic paths is often not completely ameliorated by fallowing and normal tillage operations. It is often possible to observe old tractor paths in beds because of the poor growth of seedlings in these areas. For that reason, the location of tractor paths should be considered permanent from crop to crop.

Lifters, especially those with a shaking action, can cause a compacted layer. This is especially true since they often must be used in periods of high soil moisture. This compacted layer should be ameliorated without delay; poor drainage caused by this layer may encourage saprophytic survival of water mold type pathogens such as *Pythium* and *Phytophtora* species.

Finally, there may be options in scheduling machinery use in relation to rain or irrigation. As a general rule, the potential for soil compaction increases with soil water content, with maximum compaction occurring at or slightly below field capacity. Field operations should be conducted at the lowest possible soil moisture level for machine operation. It is well known that higher amounts of soil organic matter will expand this soil moisture window.

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