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Assessment of Soil Disturbance on Farmland

Presented to

New Jersey State Agriculture Development Committee

by

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April, 2010

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Assessment of Soil Disturbance on Farmland

Purpose of the Summary

This summary was produced to assist in decision-making by the State Agriculture Development Committee (SADC) about the impact that selected farm activities have on soil characteristics, how negative impacts on soil properties may be remediated, and whether these activities should be encouraged or discouraged on New Jersey preserved farmland. New Jersey's Farmland Preservation Program consists of the purchase of development rights to parcels of land with the intention that the land use will henceforth be limited to agricultural and horticultural production. The land title is attached to a deed of easement which specifies the terms of the sale, including restrictions placed on the use of the property. Generally, non-agricultural uses are not permitted. In addition, no activity is permitted which would be detrimental to water conservation, erosion control, or soil conservation. Our intent is to discuss these issues with the acknowledgement that impacts on soils differ due to site-specific factors and properties, and that site specific remediation practices may be needed to alleviate or mitigate any negative impact on soil properties. We also present our findings and recommendations without considering the extent of disturbance (acreage) or purpose for it, but acknowledge the goal of maintaining soil quality, health and conditions that allow for current and future uses for agricultural and horticultural production.

Literature Search Limitation and Scope

Because the scientific literature on soil degradation is vast and spans many decades, continents, and climatic zones, the literature search used to develop this summary was limited to research on humid, temperate zone agriculture, similar to New Jersey conditions and soils, disregarding a sizable literature from arid and semi-arid regions as well as tropical climate regimes. In addition to the literature review findings, our professional expertise and opinions and common professional knowledge are the basis for the statements and recommendation made within.

Guidance from the New Jersey State Agriculture Development Committee (SADC)

Ranking criteria are applied when land parcels are selected for the Farmland Preservation program. Part of this ranking is a determination of the soils based on a classification system developed by the New Jersey unit of the Natural Resources Conservation Service.

- **Prime farmland** is land that has the best combination of physical and chemical characteristics (defined below) for producing food, feed, forage, fiber and oilseed crops and is also available for these uses. It has the soil quality, growing season, and moisture supply needed to economically produce sustained high yields of crops when treated and managed according to acceptable farming methods, Prime Farmlands are not excessively erodible or saturated with water for a long period of time, and they either do not flood frequently or are protected from flooding.
- Farmlands of **statewide** importance include those soils in land capability Class II and III that do not meet the criteria as Prime Farmland due to erosion hazard, wetness, or susceptibility to flooding. These soils are nearly Prime Farmland and economically produce high yields of crops when treated and managed according to acceptable farming methods. Some may produce yields as high as Prime Farmland if conditions are favorable.
- Farmland of **local** importance includes those soils that are not prime or statewide importance and are used for the production of high value food, fiber or horticultural crops.
- Farmland is classified as **unique** if it is being used for special crops production.

(Source: http://www.nj.nrcs.usda.gov/technical/soils/njfarmindex.html)

Although NJ soils are grouped into these four classifications, each individual soil's inherent properties and intrinsic agricultural productivity vary. Our approach in this analysis is to discuss specific management practices that may unintentionally or purposefully degrade soil characteristics and to make recommendation on how to remediate, when possible, any negative impacts. Any practice which results in the land no longer being tillable, or which forces a downgrade of the soil classification to more limited use, would make it less suitable for long-term agricultural sustainability and is contrary to soil conservation goals. However, soils of varying quality, or classification as listed above, will react to the impact to different degrees and may require remediation of differing types or lengths of time to be effective.

Soil Quality and Sustainability in Agriculture

Soil quality is defined as "the capacity of a specific kind of soil to function, within natural or managed ecosystem boundaries, to sustain plant and animal productivity, maintain or enhance water and air quality, and support human health and habitation" (USDA-NRCS, 2007). Considering the focus on function, specific functions of concern should be defined in advance when applying the concept of soil quality. Soil quality concepts are commonly used to evaluate sustainable land management in agricultural ecosystems, and preventing a decline in soil quality is essential to the concept of sustainability in agriculture. By analogy to living systems, the relative condition and functioning of the soil ecosystem is often referred to as soil "health".

An important part of the soil quality definition is that quality is specific to each kind of soil. The quality of a soil has two distinct aspects, *inherent* quality and *dynamic* quality. Inherent quality is use-invariant and represents intrinsic properties (qualities) of soils as determined by the factors of soil formation--climate, topography, biota, parent material, and time. The inherent quality of soils is often used to compare the capabilities of one soil against another, and to evaluate the worth or suitability of soils for specific uses.

Soil Quality as Influenced by Management

In contrast with *inherent* soil quality, which derives from soil-forming factors, *dynamic* soil quality can vary depending on how the land is managed. Management choices affect the amount of soil organic matter, soil structure, soil depth, water and nutrient holding capacity (USDA-NRCS, 2007). These in turn affect soil functions relevant to agriculture in general and to this study in particular, such as i) food and biomass production (include physical support of plants and habitat for roots), ii) storing, filtering and transformation of matter and energy (water, nutrients and organic matter) and iii) biological habitat and gene pool.

Use-dependent effects most often manifest in surface and near-surface layers result in an increase (aggradation), decrease (degradation) or sustained capacity of a soil to perform the functions listed above. The soil properties considered most representative of the overall soil health or quality include: organic matter content, soil structure, bulk density, infiltration rate, and activity of the biological community. Collectively, management will aggrade, sustain or degrade the quality of the soil. Management practices and uses of the land that have a positive (aggrading) effect on soil quality include for instance those practices leading to an increase in organic matter content. On the other hand, management practices causing compaction, erosion, or acidification have a degrading effect on soil quality and result in an increased input to maintain plant growth; thus precluding the concept of sustainability. A similar set of functions would apply to animal agriculture with additional functions related to waste management.

Soil quality can be evaluated relative to a standard or reference condition that represents the full capacity of that soil to function for a specific use. Several systems have been developed to evaluate soil quality and soil health, and numeric soil quality indices have been created to facilitate a comparison of one soil against another as well as to evaluate the change in quality expected from a change in management. The limitation that a given soil can only be compared to its own full potential, or to another soil of the same inherent properties, remains. This is especially relevant to New Jersey soils which vary greatly in their inherent quality from one region and physiographic province to another. Therefore, while a condensation of soil quality into a single value may be of limited practical value, the exercise of assessing relative change in the important soil properties can be a useful tool in guiding decisions for management. In order to make decisions about management practices, a NRCS soil management plan could be used to assess if a planned practice or use will significantly destroy or impair soil quality, and include a remediation plan to restore the affected characteristic or factor.

Compaction

Soil structural integrity is always part of the minimum data set for the evaluation of soil quality, and compaction with its damage to soil structure and/or tight packing of soil particles is the most widespread kind of soil physical degradation across all soil textures**.** It is recognized as a ubiquitous problem in the agriculture of all temperate-zone industrialized countries. The degree and depth of the disturbance by compaction, as well as soil type, influences whether a remedy is possible or feasible, or whether the damage is permanent.

To the extent that soil drainage is impaired, compacted soils are relatively wet in the spring which slows soil warming and results in delayed planting. Equipment and fuel requirements for tillage of compacted soil are increased. Winter freezing/thawing cycles are only minimally helpful at alleviating compaction and only near the surface. The major consequences of agronomic compaction are summarized below.

Soil structure is destroyed.

- Soil aggregates of structured soils are destroyed, and particles are re-oriented into platy structure (having primarily horizontal fissures) or kneaded into a high-strength mass. Subsequent tillage may break the mass into clods but does not restore the original structure. In coarse-textured soils, particles are forced into a close-packing arrangement, and pore size distribution is proportionately affected.
- Total pore space of the soil is decreased.
- Larger pores, which function as conduits for water, air, and roots, are preferentially destroyed, decreasing permeability, aeration, and root growth. Not only size but also continuity of pores is reduced.

Plant growth is negatively affected.

- Cool, wet soils (as may result from poor drainage of compacted soils) delay planting and reduce and slow germination and crop development.
- Roots are prevented from proliferating in the topsoil and extending to the subsoil because of high soil strength (resistance to penetration).
- Crops with limited root systems are unable to take up adequate water and nutrients and are susceptible to induced drought, nutrient deficiencies, and aeration stress.
- Plants are stunted and display delayed development.
- Stressed plants are susceptible to disease and insect damage.
- Crop yields are reduced.

Natural hydrology is circumvented.

- Reduced macro-pore-space results in poor infiltration and can result in excess puddling and/or increased runoff volumes and rates. Weight of construction equipment corresponding to differing levels of compaction is not as important to infiltration rate as whether compaction occurred at all, with compacted soil effectively acting as an impervious surface (Gregory, et al, 2006).
- Increased water volume in storm drains and streams leads to flooding hazards.
- Groundwater recharge is reduced along with stream base flow during dry periods.
- Supply of fresh water is decreased.
- Even in cases where topsoil compaction is relieved and water can infiltrate, subsoil compaction limits internal drainage. "Perched" water in the soil profile can create anaerobic zones, presenting further risks to roots, and increases susceptibility of topsoil to erosion.

Increased water runoff poses a water pollution hazard.

- Increased water runoff speed and volume results in increased chemical as well as biological contaminant load to streams and other water bodies.
- Risk of soil erosion increases with increasing runoff.
- Soil particles themselves ("suspended solids") are detrimental to water quality but also transport nutrients (especially phosphate) which can be pollutants.

Soil compaction is not easily or rapidly remedied.

- Surface tillage treats - but does not remediate - surface (8-10") compaction.
- Tillage after compaction yields clods rather than aggregates; additional tillage is needed to break up clods and smooth ground to create a seedbed. Broken up clods still do not function physically or biologically like naturally formed aggregates.
- Because of tillage-induced loss of soil strength, "loosening inevitably brings the risk of greater subsequent compaction" (Gabriels, *et al*., 1997).

Biological amelioration has been used for long-term treatment.

- Roots of grasses and deep tap-rooted crops help penetrate compacted layer.
- Tree roots can penetrate highly compacted soil (1.6 g cm^{-3} clay loam) and increase infiltration rates under experimental conditions (Bartens et al., 2008).
- Organic matter amendments promote earthworm populations and other soil organisms, whose activities loosen the soil and re-create structure.
- Treatment may entail years of remediation effort and expense without a saleable crop and reduced yields until soil conditions improve.

Compaction often reaches subsoil (12-20" or more), beyond the reach of normal tillage operations.

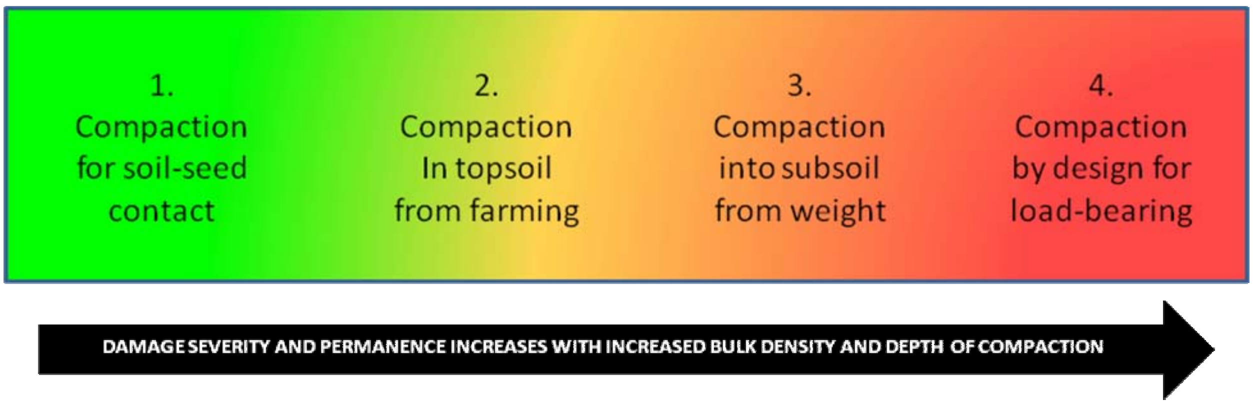
- Subsoil "ripping" or deep tillage would be required to break up deep compaction, requiring special equipment and high energy expenditure.
- Limited area is treated per pass.
- As with surface tillage, there is "risk of greater subsequent compaction".
- Subsoil compaction is a long-term and possibly unsolvable problem; depending on degree of compaction, recovery may require from 3 to 9 or more years, or the damage may be permanent. Deliberate compaction, particularly with vibratory forces, increases the depth and degree of compaction possible.
- Maximum compaction (or optimal compaction sought by engineers of loessial silt loam can result in density of about 105 pounds per cubic foot, about equal to 1.68 g/cm^3 or 36.6% total porosity. Compare this to "ideal" soil density for plant growth: 50% porosity, 1.32 g/cm^3.
- Vibratory compaction (applying dynamic or time-variable load) is a more "efficient" (severe) method of compaction than static loading.
- There is no reference to attenuation time of a compacted condition for engineering purposes. The assumption is that when done well, it will not loosen naturally--it is a permanent change.
- Soil compaction for engineering purposes results in a nearly impermeable surface or layer.

Compaction as a Continuum

An idealized soil in good agronomic condition is often depicted as having 50% of its volume occupied by soil mineral and organic matter and 50% of its volume consisting of pore space. This pore space may be occupied primarily by air or water or a combination of both in relative amounts depending on recent precipitation, internal drainage, and uptake of water by plants rooted in the soil.

As illustrated in Figure 1, there is a continuum of degrees of compaction ranging from light compaction needed to prepare a seedbed (level 1) to severe compaction designed for engineering purposes and that would preclude plant growth without remediation practices (level 4).

Figure 1. Degrees of soil compaction often encountered in agricultural operations, ranging from mild (1) to most severe (4).



A description of those compactions levels follow:

1. Acceptable compaction occurs after tillage and planting, where soil is pressed against the newly planted seed. Good contact between soil and seed is important for germination, keeping soil moisture in contact with the seed. These types of compaction are understood to be acceptable and necessary for many types of agricultural production.
2. Compaction in the topsoil resulting from field operations beyond primary and secondary tillage. This category of compaction is negative and unintended, but difficult to avoid. It can be partially remedied by management options of two kinds: i) additional field operations or practices, such as planting of cover crops and green manures for the purpose of improving soil structure, or ii) acceptance of reduced crop yield. The extent of impact is greatly dependent on site-specific soil properties including soil texture, soil moisture conditions, and production practices being used.
3. Compaction that extends beyond the topsoil and into the subsoil may be beyond economically feasible remediation, depending on the depth of the damage. In an agronomic setting, the topsoil is the Ap horizon, and its depth is determined by the reach of conventional tillage equipment, up to approximately 30 cm or 12 inches. Where the depth of subsoil compaction is no more than 50-60 cm or 20-24 inches, possible remedies may include a lengthy rotation with deep, tap-rooted species in combination with the contracting of specialized subsoiling operations. Each carries a substantial direct or opportunity cost which may make any remedy unfeasible, depending on the value of the land in full production. Subsoil compaction is normally considered permanent damage, and may be manifested in reduced crop yields, impeded root growth, and decreased water percolation.
4. Deliberate compaction of soil in the context of structural engineering and slope stabilization is more drastic still. No overlap is found between the appropriate compaction required for field production and the engineering compaction specified for load-bearing construction. The literature does not consider the effects of such extreme compaction on crop yield since the context and intent in such cases is a permanent conversion of soil as a growth medium to soil as an

engineering medium. For instance, deep tillage is used to alleviate compaction on mined sites, but when this practice is used for reclaiming severely compacted soils to plant forest, the return on the investment could be neutral to negative (Sweigard et al., 2007). In agriculture enterprises, the acreage that is converted to this state should be minimized if the objective is to maintain as much of the preserved farmland in a productive and quality state. This limitation however may exclude specific practices that are necessary for some types of agricultural production; our intent is to solely discuss this from a soil quality and health standpoint.

Focus of Research on Compaction and Remediation

Research on agricultural compaction is normally undertaken to minimize it, prevent it, remediate it, measure it, or compute yield reduction and other damages resulting from it. No research literature was found on the subject of site remediation following intentional compaction for engineering/construction purposes (level 4 as described above). Some literature exists on restoration of normal hydrologic function to unpaved logging roads in forests, on remediation and restoration following military training operations, and on remediation of utility rights of way through agricultural areas. Land reclamation following surface mining may provide a good indication of the magnitude of the restoration required following compaction for structural engineering purposes. This is extraordinarily costly restoration requiring specialized equipment not normally associated with agriculture. While it may be technically possible, in the absence of any budgetary limitation, to restore land productivity following such drastic disturbance, it is not considered feasible given any reasonable level of expected economic return (ten-year-old numbers range from $5000 to $20,000 and more per acre).

Compaction is not always recognized by the land user as a source of yield reduction. When land is partially degraded but still producing an economic yield, the land manager will typically modify his management to compensate for whatever is limiting to production. In many cases, rather than resulting in a reduction of yield, compaction damage manifests in the need for increased energy use, more frequent field operations, and higher fertilizer and water use - increased inputs which would not be needed in well-structured soil.

Subsoil compaction, below the depth of 30 cm or 12 inches (tillage depth), is usually considered a permanent degradation of agricultural land. The literature is full of statements that subsoil compaction must be avoided rather than remedied. As with land restoration following strip-mining, this may reflect the extreme cost of restoration rather than a declaration that no remedy is physically possible. Costs of restoration of desirable soil properties include the financial costs of soil amendments, labor, equipment, fuel and reduced yields. In addition, natural processes that improve soil, such as biological activity, soil aggregation, etc. depend also on time and site specific conditions that influence rates of improvement.

Specific Farm Practices

Most practices cannot be called destructive or constructive without knowledge of the impact of that practice on the soil resource of a specific site. For example, “leveling” which did not reduce the thickness of the topsoil could be a relatively benign operation of topsoil grooming used to increase infiltration if its use reduces overland flow. Alternatively, “leveling” could be highly destructive, such as a situation in which the entire topsoil horizon is penetrated or removed to match the elevation of some other point in the level plane. For this reason we focus on the extent of the soil disturbance resulting from the practice rather than the type of practice itself. Site-specific knowledge is needed to determine if a practice on a given site would cause a level of disturbance and reduction of soil quality that are incompatible with soil conservation.

Tillage is generally accepted as a routine and acceptable agricultural practice. However, tillage usually results in some degradation of soil quality because it breaks down soil structure, compacts soil, and decreases certain populations of soil organisms. This must be balanced with the necessity of tilling soil to prepare the soil for the crop. On the other hand, the necessity of tilling is over-estimated by the farmer in many cases, and the soil disturbance by excessive tillage (again, a matter of degree) degrades soil quality more than necessary to grow the crop. Therefore minimization of the frequency of soil tillage (using minimum tillage to no-tillage practices) or the use of less destructive implements (moldboard or chisel plow versus rototiller) is recommended when possible.

Geotextiles are sometimes used in specialty crop production systems in New Jersey; and little if any information is available regarding their effects on biological/microbial properties of the underlying soil. As with the example of land leveling, it is the degree of attendant soil disturbance and not merely the use of geotextile that determines the effect of this kind of disturbance. Factors that can be expected to relate to effects of geotextile use on underlying soil include: relative infiltration and/or aeration/evaporation rates; traffic loads applied, placement of gravel/stone over geotextile, and type of geotextile. Despite the lack of specific research on the impact of geotextiles on soil properties, basic concepts of soil science can be used to deduce possible results. If used only as a weed-blocking cover over undisturbed soils, geotextile cover of soil might lead to a gradual reduction in soil organic matter (as oxidation occurs without any input of organic matter from growing plants) and subsequent consequences. It might be expected that this, and the resulting reduction in soil quality, can be remedied by removing the textile and using practices to increase organic matter levels.

Increasing soil organic matter levels (carbon) is essential, however, it is difficult to access the rate of accumulation with soil building practices. The amount of increase over time varies depending on the type of management practices employed. These include reduced tillage intensity, increased crop rotation complexity, inclusion of legumes in rotation, inclusion of winter cover crops, efficient use of fertilizers, pesticides and irrigation, and erosion reduction (Paustian et al., 2007; West and Post, 2002), as well as manure management, effective crop species selection (Conant et al, 2001) or the addition of non-traditional materials such as non-composted municipal leaves (Heckman and Kluchinski, 2000). The rate of organic matter accumulation, or loss, varies due to the type of management that impacted the soil originally, the soil's inherent properties and current status, climate and other factors. This ideally requires *in situ* measurement over time to determine impacts. Carbon Management Response curves are reported as useful tools (West et al., 2004) to estimate the loss and gain of carbon between changes in land use, but none of the specific farm practices of concern are included in this work.

Regardless, organic matter is undoubtedly accumulating in the soil when above practices are utilized. The organic matter values may not show significant increases for many years, but improvement in physical soil properties such as aggregation and moisture holding can be realized. Research in New Jersey found 3 consecutive annual applications of 10 and 20 dry tons/A of municipal leaf waste increased soil organic matter levels 0.5 to 0.7% (Heckman and Kluchinski, 2000) one year after the final application. These high rate applications of high carbon material are atypical and suggest that green manures or cover crops use would increase levels at a much lower rate. Therefore, organic matter levels may increase slightly over several years but potentially could take decades of sound management. However, the benefits of any small increase would be manifested in improvements several soil properties. Therefore it is difficult to provide a specific time frame necessary to restore soil organic matter levels to initial or higher levels.

Seasonal use of impervious cover over undisturbed soil where the soil is being used in its existing condition as the growth medium (high tunnel hoop houses): High tunnel usage continues to increase throughout the country in areas where climatic crop producing limitations can be overcome, essentially allowing for growing season extension in the spring and fall months. The construction, unlike permanent greenhouses, does not involve the compaction or excavation of soil to build or pour concrete foundations. Rather, wood framing is used to establish a based to which PVC tubes driven into the ground and looped to the opposite side of the frame are attached. Once the support structure is completed, polyethylene greenhouse covering is attached. Our professional assessments is the main impact of this situation will be the limitation of precipitation (presumably rainfall) infiltrating and passing through the soil. Principles of water conservation, as well as economic motivation, will limit irrigation to what is necessary to keep the root zone moist for plant growth and is unlikely to allow leaching to groundwater. The increased soil temperatures may be sufficient to increase soil biological activity; this may enhance nutrient availability but increase oxidation and loss of soil organic matter. Stormwater management may be necessary to handle excess water attempting to infiltrate/runoff the areas surrounding the impervious structures. Steps to remediate any negative impact on soil properties are minimal; the return to traditional agricultural production (*sans* hoop house) can be easily achieved and management practices such as introduction of organic materials into the soil will remediate any loss of soil organic matter.

Long term use of impervious cover (high tunnel hoop houses for two years or more): This situation is between those described above and below; effects will depend on time and specific practices.

Long term impervious cover (roof) over undisturbed soil: Based on our professional assessment and/or cited research, the potential limitations that a roof imposes on natural soil processes are the amount and quality of sunlight, and the amount and quality of water passing through. Certain situations (glass houses) may allow direct sunlight, while opaque roofs will allow only indirect sunlight or artificial light underneath. Light limitation will affect plant growth and therefore organic matter addition and microbiological population and activity in the soil. Elimination of natural precipitation from soil may or may not have an effect, depending on other management factors. Frequent irrigation may allow similar total amounts of water as expected in precipitation (about 40" in New Jersey), but it is likely that rarely would the soil experience near-saturation conditions that cause leaching through the soil profile to groundwater. This could be expected to become a problem when/if fertilizing, as in glasshouse or hoop house situations. Routine application of fertilizer without leaching water application can lead to salt build-up (salinity), another form of soil degradation not normally encountered in New Jersey's humid climate but common in agriculture of arid regions. Remediation steps would include the reintroduction of organic materials to increase soil aggregation and other physical properties and biological activity. Rainfall and irrigation, and use of soil amendments such as gypsum, would help to leach any accumulated salts over time, most likely over several months or a year or two, depending on the level of salt accumulation, rainfall patterns, and soil permeability and drainage.

Permanent structure and long term impervious cover with soil substantially disturbed (including geotextile, alone, geotextile with gravel cover, or concrete foundation): When the function of a soil is strictly an engineering media, there are wholly different sets of quality criteria. They would include optimum water content (for compaction), compressibility, bearing capacity, shrink-swell behavior, strength, (etc.). The quality indicators for the engineering function are by necessity contrary to those for the cropping (food and biomass production) and hydrology functions of soil. In particular, soil compaction is necessary to provide a stable base for a permanent structure. For that reason, effort is made to compact soil to the greatest degree and depth possible (and in the process, destroy naturally developed soil structure) or to remove any of the soil that may impede providing such a base. The densified soil underneath a permanent structure (impervious cover) may still contain organic matter, and that content may remain relatively constant considering conditions conducive to limited decomposition while organic matter additions are precluded by the built structure. The impervious nature of the structure and the compaction required to build it prohibits the soil from infiltrating, filtering, and passing precipitation to groundwater, so that all precipitation impacting the structure and the surrounding affected soil have to be controlled by otherwise-unnecessary stormwater devices/structures.

Geotextile and geotextile with gravel cover could actually mitigate the negative effects, but concrete foundation "seals" the fate of the entombed soil. Recently evolving study of urban soil provides data to predict concrete's effects. The classification system being developed for urban soils, expanding on the classification systems for "natural" soils, includes "Technosols" whose development and properties are dominated by their extensive disturbance by man (Schwartz et al. 2009). Sealing of soil by concrete, which also occurs on farmland, qualifies a soil as a Technosol. The imperviousness of this type of Technosol and its effects on infiltration, runoff, and water pollution is not the only effect; pH of the soil underlying the concrete and its subsequent or concomitant effect on geochemical cycles and biological activity (Charzynski et al., 2009) are additional factors that alter soil functions in the long term. For example, pH approaching 8.3 negatively affects most agricultural and horticultural crops.

Remediation under these conditions would be more difficult and costly. After the removal of any structures and debris, specialist deep-tillage equipment requiring significant energy and time inputs may allow for cultivation of the soil and incorporation of soil organic amendments. Over time, the status of the soil may improve to the point where some crop yields would be expected but they would be less than similar undisturbed soils. The primary impacts would be that the majority of the soils' inherent characteristics are negatively impacted and its profile would be permanently and negatively altered. Therefore, to preserve the soil in its natural state, or to lessen the impact of such practices, the extent of disturbance (acreage) should be limited or the purpose for it justified in a soil management plan.

Long-term impact of outdoor equine training tracks*:* The construction of equine training tracks may involve grading (leveling and/or smoothing), compacting the soil base, and layering with desirable footing material. Subsequent management includes tractor-mount raking and rolling to eliminate vegetation and to smooth and firm the surface. Spraying the surface with water when dry is typical to control dust and prevent wind erosion. The effects on underlying soil would include primarily compaction of the soil by both horse and tractor traffic. The surface soil texture is likely to be affected when the original soil is fine-textured or loamy; these soil types are most likely to have addition of footing material due to requirement for rapid infiltration/permeability and susceptibility to compaction when wet and hardness when dry (whereas sandy soil is inherently more suitable because of rapid water infiltration/permeability and poor cohesiveness). Organic matter content of the soil will be depleted as the original humus is oxidized and the only input is limited to the occasional manure pile. The surface of the (non-vegetated) track is likely to experience erosion by water during rainstorms and by wind when dry. Turf tracks are better protected from erosive forces, but additional management requirements are necessary to maintain the turf as a "crop" (nutrient levels, irrigation, etc.). Remediation steps would include the reintroduction of organic materials to increase soil aggregation and other physical properties and biological activity.

Impact of Practices on Soil Functions and Potential for Remediation

A qualitative summary of the practices discussed and their impact on selected soil functions is presented in Table 1. The matrix can serve as an initial comparison among practices. The assessment of impact of each practice is expected to vary with soil type and would need to be validated with either additional data or modeling.

As outlined, there is a continuum of impacts for any soil function (Table 1). Soil under almost any condition can be improved, but there is potential for a loss of productivity if the soil structure has been irreparably harmed. The determination of what is "acceptable" and "unacceptable" soil disturbance can only be established through research involving the set of practices under consideration and the soil and climate conditions in New Jersey. Most minor to significantly negative practices can be remediated through various cultural practices, however increasing costs (time, money) may be prohibitive and crop yield or quality may be depressed for periods of time.

Table 1. Summary of the relative impact of practices on selected soil functions and their potential for remediation[1]

Practice	Soil Functions			Potential for Remediation[2]
	Food and Biomass Production	Storing, Filtering and Transformations	Biological Habitat and Gene Pool	
Geotextiles	Very negative (no biomass production)	Limited reduction of biological activity and of exchanges of matter and energy with the atmosphere.		Medium to High
Impervious Cover-Seasonal	Enhanced (biomass production augmented)	Limited negative or neutral impact due to short time scale.		Very High
Permanent Structures	Very negative impact on all soil functions			Very Low
Outdoor Equine Training Tracks	Very negative impact on all soil functions			Low

[1] Based on the authors' professional judgment and experience as no specific research on the impact of the listed practices was found in the literature review.

[2] Potential for remediation is based on the degree of alteration of soil properties and do not consider the spatial extent of soil modification introduced by a given practice.

References

_____. 1994. Soil Compaction in Crop Production. Series: Developments in Agricultural Engineering 11, Editors: Soane, B. D. and Van Ouwerkerk, C. Amsterdam, The Netherlands: Elsevier Science B. V.

_____. 2001. Farming Today for Tomorrow. Video lecture series on sustainable agriculture. Oregon State University, Corvallis, OR.

_____. 2001. Land Disturbance Ordinance, Draper City, Utah.

_____. 2004. Citizen's Guide to Farmland Reclamation. Office of Mines and Minerals, Land Reclamation Division, Illinois Department of Natural Resources. Springfield, Illinois.

_____. 2004. Standards for the Farmland Preservation Program. Rock County, WI: Rock County Land Conservation Committee.

_____. 2005. Soil Restoration: BMP 26. Water Quality Division, Idaho Department of Environmental Quality. Boise, ID.

_____. 2006. Urban Soil Compaction and Storm Water Runoff. Newsletter "On the Land". Valley View, Cuyahoga Soil and Water Conservation District, Valley View, OH.

_____. 2006. BMP 6.7.3: Soil Amendment and Restoration. Pennsylvania Stormwater Best Management Practices Manual, PA Department of Environmental Protection.

_____. 2007. Restoring Compacted Soil. Fact sheet produced by Sound Native Plants, Olympia, WA.

_____. 2007. Land Restoration After Pipeline Construction. Pamphlet of Iowa Utilities Board, Des Moines, IA.

_____. 2007. Section 2E-5: Soil Quality Restoration. In: Iowa Stormwater Management Manual. Iowa State University, Ames, Iowa.

_____. 2008. Construction Standard for: Backfill and Compaction for 16" and Smaller Water Main Trenches. METROPOLITAN UTILITIES DISTRICT, Omaha, NE.

_____. 2008. Glossary of Soil Science Terms. Soil Science Society of America, Madison, WI.

_____. undated. Guide to Sampling Soil Compaction Using Hand-Held Soil Penetrometers. Center for Environmental Management of Military Lands, Colorado State University, Fort Collins, CO.

_____. undated. Military Soils Engineering. U.S. Army Field Manual, US Army Corps of Engineers.

_____. undated. Soil Compaction Handbook. Trade publication of Multiquip, Inc., Carson, CA.

Adams BA and Wulfsohn D. 1998. Critical-state behaviour of an agricultural soil. Journal of Agricultural Engineering Research 70(4):345-354.

Ahuja LR. 2003. Quantifying agricultural management effects on soil properties and processes. Geoderma 116(1-2):1-2.

Ahuja LR, Ma LW and Timlin DJ. 2006. Trans-disciplinary soil physics research critical to synthesis and modeling of agricultural systems. Soil Science Society of America Journal 70(2):311-326.

Alakukku L. 1996. Persistence of soil compaction due to high axle load traffic. II. Long-term effects on the properties of fine-textured and organic soils. Soil and Tillage Research 37:223-238.

Al-Dousari AMRM, S. Shahid. 2000. Soil compaction and sealing in Al-Salmi area, western Kuwait. Land Degradation and Development 11(5):401-418.

Aragon A, Garcia MG, Filgueira RR and Pachepsky YA. 2000. Maximum compatibility of Argentine soils from the Proctor test; The relationship with organic carbon and water content. Soil and Tillage Research 56(3-4): 197-204.

Arnalds A. 2005. Approaches to landcare - A century of soil conservation in Iceland. Land Degradation and Development 16(2): 113-125.

Arvidsson J. 1998. Influence of soil texture and organic matter content on bulk density, air content, compression index and crop yield in field and laboratory compression experiments. Soil and Tillage Research 49:159-170.

Arvidsson J and Håkansson I. 1996. Do effects of soil compaction persist after ploughing? Results from 21 long-term field experiments in Sweden. Soil and Tillage Research 39:175-197.

Bachmann J, Contreras K, Hartge KH and MacDonald R. 2006. Comparison of soil strength data obtained in situ with penetrometer and with vane shear test. Soil and Tillage Research 87(1):112-118.

Bailey AC and Johnson CE. 1989. A Soil compaction Model for Cylindrical Stress States. Transactions of the ASAE 32(3):822-825.
Bailey AC, Johnson CE and Schafer RL. 1984. Hydrostatic Compaction of Agricultural Soils. Transactions of the ASAE:952-955.
Ball BC, D. J. Campbell, J. T. Douglas, J. K. Henshall, M. F. O'Sullivan,. 1997. Soil structural quality, compaction and land management. European Journal of Soil Science 48(4):593-601.
Barnes KK, Carleton WM, Taylor HM, Throckmorton RI and Vandenberg GE. 1971. Compaction of Agricultural Soils. American Society of Agricultural Engineers, St. Joseph, MI.
Bartens J, Day SD, Harris JR, Dove JE, and Wynn TM. 2008. Can urban tree roots improve infiltration through compacted subsoils for Stormwater management? J. Environ. Qual. 37:2048-2057.
Batey T, and McKenzie, DC. 2006. Soil compaction: identification directly in the field. Soil Use and Management 22(2):123-131.
Benjamin JG, Nielsen DC and Vigil MF. 2003. Quantifying effects of soil conditions on plant growth and crop production. Geoderma 116(1-2):137-148.
Blackwell PS and Soane, BD. 1981. A method of predicting bulk density changes in field soils resulting from compaction by agricultural traffic. European Journal of Soil Science 32(1):51-65.
Boels D, Davies DB and Johnston AE. 1982. Soil Degradation: Proceedings of the Land Use Seminar on Soil Degradation (Wageningen, 13-15 October 1980). Rotterdam, The Netherlands: A.A. Balkema.
Botta GF, Jorajuria D, Balbuena R, Ressia M, Ferrero C, Rosatto H and Tourn M. 2006. Deep tillage and traffic effects on subsoil compaction and sunflower (Helianthus annus L.) yields. Soil and Tillage Research 91(1-2):164-172.
Brady N and Weil R. 2002. The Nature and Properties of Soils,13th ed. Prentice-Hall (Pearson Education, Inc.), Upper Saddle River, NJ
Braunack MV, Hewitt JS and Dexter AR. 1979. Brittle Fracture of Soil Aggregates and the Compaction of Aggregate Beds. European Journal of Soil Science 30(4):653-667.
Brown D, Hallman RG, Lee CR and Skogerbee JG. 1986. Reclamation and Vegetative Restoration of Problem Soils and Disturbed Lands. Noyes Data Corporation, Park Ridge, NJ.
Cambardella CA, Moorman TB, Andrews SS and Karlen DL. 2004. Watershed-scale assessment of soil quality in the loess hills of southwest Iowa. Soil and Tillage Research 78(2):237-247.
Carter MR. 2002. Soil Quality for Sustainable Land Management: Organic Matter and Aggregation Interactions that Maintain Soil Functions. Agronomy Journal 94:38-47.
Cetin H. 2004. Soil-particle and pore orientations during consolidation of cohesive soils. Engineering Geology 73(1-2):1-11.
Chamen WCT. 1996. Soil compaction in crop production. Soil and Tillage Research 37(2-3):201-207.
Chaplin J, Min M and Pulley R. 2008. Compaction Remediation for Construction Sites. Report of Minnesota Department of Transportation, St. Paul, MN.
Charzynski P, Bednarek R, Nowak A, Pokojska-Burdziej A. 2009. Properties and genesis of Ekranic Technosols of Torun airport. Soils of Urban, Industrial, Traffic, Mining and Military Areas 5th International Conference. New York City, Sep. 20-25, 2009.
Chong S-K and Cowsert PT. 1997. Infiltration in reclaimed mined land ameliorated with deep tillage treatments. Soil and Tillage Research 44:255-264.
Coder KD. 2000. Soil Compaction Impacts On Tree Roots. Warnell School of Forest Resources, University of Georgia Extension.
Conant, RT, K Paustian, and ET Elliott. 2001. Grassland management and conversion into grassland: effects on soil carbon. Ecological Applications 11:343-355.
Cook FJ and Knight JH. 2003. Oxygen transport to plant roots: Modeling for physical understanding of soil aeration. Soil Science Society of America Journal 67(1):20-31.
Cowell SJ and Clift R. 2000. A methodology for assessing soil quantity and quality in life cycle assessment. Journal of Cleaner Production 8(4):321-331.
Curran MP, Miller RE, Howes SW, Maynard DG, Terry TA, Heninger RL, Niemann T, van Rees K, Powers RF and Schoenholtz SH. 2005. Progress towards more uniform assessment and reporting of soil

disturbance for operations, research, and sustainability protocols. Forest Ecology and Management 220(1-3):17-30.
Daddow RL and Warrington GE. 1983. Growth-Limiting Soil Bulk Densities as Influenced by Soil Texture. Watershed Systems Development Group: USDA Forest Service, Ft. Collins, CO.
Daniels TL. 2004. Farmland Preservation Policies in the United States: Successes and Shortcomings. Department of City and Regional Planning, University of Pennsylvania.
Defossez P and Richard G. 2002. Models of soil compaction due to traffic and their evaluation. Soil and Tillage Research 67(1):41-64.
Defossez P, Richard G, Boizard H and O'Sullivan MF. 2003. Modeling change in soil compaction due to agricultural traffic as function of soil water content. Geoderma 116(1-2):89-105.
DeJong-Hughes J, Moncrief JF, Voorhees WB and Swan JB. 2001. Soil compaction: Causes, effects and control. Report # FO-03115. University of Minnesota Extension.
Dexter AR. 1997. Physical properties of tilled soils. Soil and Tillage Research 43:41-63.
Dexter AR. 2004. Soil physical quality: Part I. Theory, effects of soil texture, density, and organic matter, and effects on root growth. Geoderma 120(3-4):201-214.
Dexter AR. 2004. Soil physical quality: Part II. Friability, tillage, tilth and hard-setting. Geoderma 120(3-4): 215-225.
Dexter AR. 2004. Soil physical quality: Part III: Unsaturated hydraulic conductivity and general conclusions about S-theory. Geoderma 120(3-4):227-239.
Dexter AR and Czyz EA. 2007. Applications of S-Theory in the Study of Soil Physical Degradation and its Consequences. Land Degradation and Development 18(4):369-381.
Diack M and Stott DE. 2001. Development of a Soil Quality Index for the Chalmers Silty Clay Loam from the Midwest USA. In: Sustaining The Global Farm. p. 550-555., International Soil Conservation Organization.
Drewry JJ. 2006. Natural recovery of soil physical properties from treading damage of pastoral soils in New Zealand and Australia: A review. Agriculture, Ecosystems and Environment 114(2-4):159-169.
Duiker SW. 2007. Soil Management. In: Agronomy Guide 2007-2008. Penn State University
Ess DR, Vaughan DH and Perumpral JV. 1998. Crop Residue and Root Effects on Soil Compaction. Transactions of the ASAE 41(5):1271-1275.
Faechner T, Pyrcz M and Deutsch CV. 2000. Soil remediation decision making in presence of uncertainty in crop yield response. Geoderma 97(1-2):21-38.
FAO. 1977. Assessing Soil Degradation. Rome: FAO Soil Bulletin 34.
Freese RC, Cassel DK and Denton HP. 1993. Infiltration in a Piedmont Soil Under 3 Tillage Systems. Journal of Soil and Water Conservation 48(3):214-218.
Fritton DD. 2008. Evaluation of pedotransfer and measurement approaches to avoid soil compaction. Soil and Tillage Research 99(2):268-278.
Gabriels D, Horn R, Villagra MM and Hartmann R. 1997. Assessment, prevention, and rehabilitation of soil structure caused by soil surface sealing, crusting, and compaction. . In: Advances in Soil Science: Methods for Assessment of Soil Degradation. CRC Press, Boca Raton, FL
Galan MB, Peschard D and Boizard H. 2007. ISO 14 001 at the farm level: Analysis of five methods for evaluating the environmental impact of agricultural practices. Journal of Environmental Management 82:341-352.
Gallipoli D, Gens A, Chen G and D'Onza F. 2008. Modelling unsaturated soil behaviour during normal consolidation and at critical state. Computers and Geotechnics 35(6):825-834.
Gameda S, Raghavan GSV, McKyes E and Theriault R. 1987. Subsoil Compaction in a Clay Soil .2. Natural Alleviation. Soil and Tillage Research 10(2):123-130.
Gameda S, Raghavan GSV, McKyes E and Therieault R. 1987. Subsoil compaction in a clay soil. I. Cumulative effects. Soil and Tillage Research 10:113-122.
Gassman PW, Erbach DC and Melvin SW. 1989. Analysis of Track and Wheel Compaction. Transactions of the ASAE 32(1):23-29.

Gerowitt B, Isselstein J and Marggraf R. 2003. Rewards for ecological goods--requirements and perspectives for agricultural land use. Agriculture, Ecosystems and Environment 98(1-3):541-547.
Gilman EF. 2007. Critical Bulk Density Values. In Series: Landscape Plants. University of Florida.
Gliński J and Lipiec J. 1990. Soil Physical Conditions and Plant Roots. Boca Raton, FL: CRC Press, Inc.
Goldsmith W, Silva M and Fischenich C. 2001. Determining Optimal Degree of Soil Compaction for Balancing Mechanical Stability and Plant Growth Capacity. Report # ERDC-TN-EMRRP-SR-26. U.S. Army Engineer Research and Development Center, Vicksburg, MS.
Gray DH. undated. Optimizing Soil Compaction and Other Strategies. Grading and Excavation Contractor. Forester Press, Santa Barbara, CA.
Green TR, Ahuja LR and Benjamin JG. 2003. Advances and challenges in predicting agricultural management effects on soil hydraulic properties. Geoderma 116(1-2):3-27.
Gregory, J.H., M.D. Dukes, P.H. Jones, and G.L. Miller. 2006. Effect of urban soil compaction on infiltration rate. J. Soil Water Conservation 61:117-124.
Gresser CS. Soil Compaction and Stability. (Informational sheet on compaction) Giles Engineering Associates, Waukesha, WI.
Gupta SC and Allmaras RR. 1987. Methods to assess the susceptibility of soils to excessive compaction. Advances in Soil Science 6:65-100.
Hakansson I and Lipiec J. 2000. A review of the usefulness of relative bulk density values in studies of soil structure and compaction. Soil and Tillage Research 53(2):71-85.
Hamilton-Manns M, Ross CW, Horne DJ and Baker CJ. 2002. Subsoil loosening does little to enhance the transition to no-tillage on a structurally degraded soil. Soil and Tillage Research 68(2):109-119.
Hamza MA and Anderson WK. 2005. Soil compaction in cropping systems: A review of the nature, causes and possible solutions. Soil and Tillage Research 82(2):121-145.
Hebblethwaite PD and McGowan M. 1980. The effects of soil compaction on the emergence, growth and yield of sugar beet and peas. Journal of the Science of Food and Agriculture 31(11):1131-1142.
Heckman, JR and D Kluchinski. 2000. Agronomics of land application of municipal collected shade tree leaves: I. Soil properties. J. Sustainable Ag. The Hawthorn Press, Binghamton, NY. Vol. 17(2/3), pp. 33-40.
Heller MC and Keoleian GA. 2003. Assessing the sustainability of the US food system: a life cycle perspective. Agricultural Systems 76(3):1007-1041.
Hillel D. 1980. Fundamentals of Soil Physics. Academic Press, New York, NY.
Horn R, Domzzal H, Slowinska-Jurkiewicz A and van Ouwerkerk C. 1995. Soil compaction processes and their effects on the structure of arable soils and the environment. Soil and Tillage Research 35(1-2):23-36.
Horn R and Fleige H. 2008. Risk assessment of subsoil compaction for arable soils in Northwest Germany at farm scale. Soil and Tillage Research, in Press, from online journal, pages not assigned yet.
Hurni H. 1988. Principles of soil conservation for cultivated land. Soil Technology 1(2):101-116.
Ivey JL and McBride RA. 1999. Delineating the Zone of Topsoil Disturbance Around Buried Utilities on Agricultural Land. Land Degradation and Development 10(6):531-544.
Jones CA. 1983. Effect of Soil Texture on Critical Bulk Densities for Root Growth. Soil Science Society of America Journal 47:1208-1211.
Jones RJA, Spoor G and Thomasson AJ. 2003. Vulnerability of subsoils in Europe to compaction: a preliminary analysis. Soil and Tillage Research 73(1-2):131-143.
Karlen DL, Hurley EG, Andrews SS, Cambardella CA, Meek DW, Duffy MD and Mallarino AP. 2006. Crop rotation effects on soil quality at three northern corn/soybean belt locations. Agronomy Journal 98(3):484-495.
Kennedy LA. 2005. Is Water Reuse Sustainable? Factor Affecting its Sustainability. Arabian Journal for Science and Engineering 30(2C):13.
Kirby M. 2007. Whither soil compaction research? Soil and Tillage Research 93(2):472-475.

Kline R. 2006. Agricultural Comments on the Vancouver Island Transmission Reinforcement Project (VITRP) - Environment Assessment Certificate Application. Environmental Assessment Office, Ministry of Agriculture and Lands, Victoria, BC Canada.
Kuht J, Reintam E, Loogus, H and Nugis E. 2003. Crop Rotation Effects on Soil Quality at Three Northern Corn/Soybean Belt Locations. Agronomy Research 1(2):6.
Lal R. 2004. Agricultural activities and the global carbon cycle. Nutrient Cycling in Agroecosystems 70(2):103-116.
Lal R, Follett F, Stewart BA and Kimble JM. 2007. Soil carbon sequestration to mitigate climate change and advance food security. Soil Science 172(12):943-956.
Lal R, Iivari T, Kimble JM and Sobecki TM. 2003. Soil Degradation in the United States: Extent, Severity, and Trends. Lewis Publishers, Washington, DC.
Laloui L and Cekerevac C. 2008. Numerical simulation of the non-isothermal mechanical behaviour of soils. Computers and Geotechnics 35(5):729-745.
Langmaack M, Schrader S, Rapp-Bernhardt U and Kotzke K. 2002. Soil structure rehabilitation of arable soil degraded by compaction. Geoderma (105):141-152.
Lapwood DHGAH, J. M. Hirst,. 1967. An Effect of Soil Compaction on the Incidence of Potato Coiled Sprout. Plant Pathology 16(2):61-63.
Lavoie G, Gunjal K and Raghavan GSV. 1991. Soil Compaction, Machinery Selection, and Optimum Crop Planning. Transactions of the ASAE 34(1):2-8.
Lebert M, H. Böken and F. Glante. 2007. Soil compaction—indicators for the assessment of harmful changes to the soil in the context of the German Federal Soil Protection Act. Journal of Environmental Management 82(3):10.
Leeson JJDJC. 1983. The variation of soil critical state parameters with water content and its relevance to the compaction of two agricultural soils. European Journal of Soil Science 34(1):33-44.
Legg W and Parris K. 2007. Farm management and the environment. Journal of Environmental Management 82(3):299-301.
Lipiec J and Hakansson I. 2000. Influences of degree of compactness and matric water tension on some important plant growth factors. Soil and Tillage Research 53(2):87-94.
Lipiec J and Hatano R. 2003. Quantification of compaction effects on soil physical properties and crop growth. Geoderma 116(1-2):107-136.
Lynch DH, Voroney RP and Warman PR. 2005. Soil physical properties and organic matter fractions under forages receiving composts, manure or fertilizer. Compost Science and Utilization 13(4):252-261.
Mamedov AI, Huang C and Levy GJ. 2006. Antecedent Moisture Content and Aging Duration Effects on Seal Formation and Erosion in Smectitic Soils. Soil Science Society of America Journal 70:832-843.
Mapfumo E and Chanasyk DS. 1998. Guidelines for safe trafficking and cultivation, and resistance-density-moisture relations of three disturbed soils from Alberta. Soil and Tillage Research 46:193-202.
Marshall SE and Tokunaga A. 2006. Soil Compaction and Strength: Measurement Methods and Influences on Perennial Grass Growth. CAL-PAC Society for Range Management Symposium-Grazing for Biological Conservation.
Moebius BN, van Es HM, Schindelbeck RR, Idowu OJ, Clune DJ and Thies JE. 2007. Evaluation of laboratory-measured soil properties as indicators of soil physical quality. Soil Science 172(11):895-912.
Nasr HM and Selles F. 1995. Seedling emergence as influenced by aggregate size, bulk density, and penetration resistance of the seedbed. Soil and Tillage Research 34:61-76.
Nhantumbo ABJC and Cambule AH. 2006. Bulk density by Proctor test as a function of texture for agricultural soils in Maputo province of Mozambique. Soil and Tillage Research (87):231-239.
NJDA. SADC Standard Deed of Easement Form. From web site, retrieved 11-9-2008. State Agricultural Development Committee, New Jersey Department of Agriculture (NJDA), Trenton, NJ.
NJDA. 1997. Prioritization of Project Areas and Individual Applications. State Agricultural Development Committee, New Jersey Department of Agriculture (NJDA), Trenton, NJ.
NRCS-USDA. 2003. Soil Compaction: Detection, Prevention, and Alleviation. Agronomy Technical Note No. 17. Soil Quality Institute, Auburn, AL.

Ohu JO, Raghavan GSV, McKyes E, Stewart KA and Fanous MA. 1985. The Effects of Soil Compaction and Organic Matter on the Growth of Bush Beans. Transactions of the ASAE 28(4):1056-1061.
O'Sullivan MF, Henshall JK and Dickson JW. 1999. A simplified method for estimating soil compaction. Soil and Tillage Research 49(4):325-335.
O'Sullivan MF and Simota C. 1995. Modelling the environmental impacts of soil compaction: a review. Soil and Tillage Research 35(1-2):69-84.
Pabin J, Lipiec J, Wlodek S, Biskupski A and Kaus A. 1998. Critical soil bulk density and strength for pea seedling root growth as related to other soil factors. Soil and Tillage Research 46(3-4):203-208.
Paton TR and Humphreys GS. 2007. A critical evaluation of the zonalistic foundations of soil science in the United States. Part II: The pragmatism of Charles Kellogg. Geoderma 139(3-4):268-276.
Paustian, K, O., Andren, HH Janzen, R Lal, P Smith, G Tian, H Tiessen, M Van Noordwijk, and PC Woomer. 1997. Agricultural soils as a sink to mitigate CO2 emissions. Soil Use and Management 13:230-244.
Pitt R, Chen SE, Clark SE, Swenson J and Ong CK. 2008. Compaction's impacts on urban storm-water infiltration. Journal of Irrigation and Drainage Engineering-ASCE 134(5):652-658.
Potter KN, Torbert HA, Johnson HB and Tischler CR. 1999. Carbon storage after long-term grass establishment on degraded soils. Soil Science 164(10):718-725.
Rab MA. 2004. Recovery of soil physical properties from compaction and soil profile disturbance caused by logging of native forest in Victorian Central Highlands, Australia. Forest Ecology and Management 191(1-3):329-340.
Radford BJ, Yule DF, McGarry D and Playford C. 2001. Crop responses to applied soil compaction and to compaction repair treatments. Soil and Tillage Research (61):157-166.
Radford BJ, Yule DF, McGarry D and Playford C. 2007. Amelioration of soil compaction can take 5 years on a Vertisol under no till in the semi-arid subtropics. Soil and Tillage Research 97(2): 249-255.
Randrup TB. 1997. Soil Compaction on Construction Sites. Journal of Arboriculture 23(5):207-210.
Randrup TB and Lichter JM. 2001. Measuring Soil Compaction on Construction Sites: A Review of Surface Nuclear Gauges and Penetrometers. Journal of Arboriculture 27(3):109-117.
Reinsch TG and Grossman RB. 1995. A method to predict bulk density of tilled Ap horizons. Soil and Tillage Research 34:95-104.
Reynolds WD, Drury CF, Yang XM, Fox CA, Tan CS and Zhang TQ. 2007. Land management effects on the near-surface physical quality of a clay loam soil. Soil and Tillage Research 96(1-2):316-330.
Reynolds WD, Drury CF, Yang XM and Tan CS. 2008. Optimal soil physical quality inferred through structural regression and parameter interactions. Geoderma 146:466-474.
Rodrigues SM, Pereira ME, da Silva EF, Hursthouse AS and Duarte AC. 2008. A review of regulatory decisions for environmental protection: Part I -- Challenges in the implementation of national soil policies. Environment International In Press, Corrected Proof.
Rousseva S. 2003. Influence of a Compacted Subsurface Layer on Soil Erosion. From conference College on Soil Physics in Trieste, Italy. N. Poushkarov Research Institute for Soil Science and Agroecology.
Sauerbeck DR. 2001. CO2 emissions and C sequestration by agriculture - perspectives and limitations. Nutrient Cycling in Agroecosystems 60(1-3):253-266.
Schaffer B, Attinget W and Schulin R. 2007. Compaction of restored soil by heavy agricultural machinery - Soil physical and mechanical aspects. Soil and Tillage Research 93(1):28-43.
Schäffer BMS, R. Müller, R. Schulin,. 2007. Changes in the macro-pore structure of restored soil caused by compaction beneath heavy agricultural machinery: a morphometric study. European Journal of Soil Science 58(5):1062-1073.
Schaller FW and Sutton P. 1978. Reclamation of Drastically Disturbed Lands. ASA-CSSA-SSSA, Madison, WI.
Schjonning P, Thomsen IK, Moberg JP, de Jonge H, Kristensen K and Christensen BT. 1999. Turnover of organic matter in differently textured soils - I. Physical characteristics of structurally disturbed and intact soils. Geoderma 89(3-4):177-198.
Schröder P, Huber B, Olazábal U, Kämmerer A and Munch JC. 2002. Land use and sustainability: FAM Research Network on Agroecosystems. Geoderma 105(3-4):155-166.

Schwartz C, Lefort C, Ouvrard S, and Morel JL. 2009. How much human-made material for a Technosol? Soils of Urban, Industrial, Traffic, Mining and Military Areas 5th International Conference. New York City, Sep. 20-25, 2009.
Schwartz RC, Evett SR and Unger PW. 2003. Soil hydraulic properties of cropland compared with reestablished and native grassland. Geoderma 116(1-2):47-60.
Séré G, Schwartz C, Ouvrard S, Sauvage C, Renat J-C and Morel JL. 2008. Soil Construction: a Step for Ecological Reclamation of Derelict Lands. Journal of Soils and Sediments 8(2):130-136.
Sillon JF, Richard G and Cousin I. 2003. Tillage and traffic effects on soil hydraulic properties and evaporation. Geoderma 116(1-2):29-46.
Smart P. 1998. Deep soil compaction. Soil Use and Management 14(2):69-69.
Smith CS, McDonald GT and Thwaites RN. 2000. TIM: Assessing the sustainability of agricultural land management. Journal of Environmental Management 60:267-288.
Smith DLO. 1987. Measurement, interpretation and modelling of soil compaction. Soil Use and Management 3(3):87-93.
Smucker AJM and Erickson AE. 1989. Tillage and compactive modifications of gaseous flow and soil aeration. In: Mechanics and related processes in structured agricultural soils. Larson, W. E., editor., p.205-221. Kluwer Academic Publishers, Dordrecht, The Netherlands.
Soane BD and Van Ouwerkerk C. 1995. Implications of soil compaction in crop productionfor the quality of the environment. Soil and Tillage Research 35.
Sojka RE, Busscher WJ and Lehrsch GA. 2001. In Situ Strength, Bulk Density, and Water Content Relationships of a Durinodic Xeric Haplocalcid Soil. Soil Science 166(8):520-529.
Spoor G. 2006. Alleviation of soil compaction: requirements, equipment and techniques. Soil Use and Management 22(2):113-122.
Stone RJ and Ekwue EI. 1993. Maximum Bulk Density Achieved During Soil Compaction as Affected by the Incorporation of 3 Organic Materials. Transactions of the ASAE 36(6):1713-1719.
Sullivan P. 2004. Sustainable Soil Management: Soil Systems Guide. ATTRA - National Sustainable Agriculture Information Service.
Sweigard, R J. Burger, J, Graves, D, Zipper, C, Barton, C, Skousen, J, and Angel, P. 2007. Loosening Compacted Soils in Mined Sites. The Appalachian Regional Reforestation Initiative. Forest Reclamation Advosory No 4.
Tapela M and Colvin TS. 1998. The soil tilth index: An evaluation and proposed modification. Transactions of the ASAE 41(1):43-48.
Tekeste M, Habtzghi DH and Stroosnijder L. 2007. Soil strength assessment using threshold probability approach on soils from three agro-ecological zones in Eritrea. Biosystems Engineering 98(4):470-478.
Thilakasiri HSMG, G. Mullins, P. Stinnette, B. Jory,. 1996. Investigation of Impact Stresses Induced in Laboratory Dynamic Compaction of Soft Soils. International Journal for Numerical and Analytical Methods in Geomechanics 20(10):753-767.
Tobias S, Haberecht M, Stettler M, Meyer M and Ingensand H. 2008. Assessing the reversibility of soil displacement after wheeling in situ on restored soils. Soil and Tillage Research 98(1):81-93.
Tobias S and Tietje O. 2007. Modelling experts' judgments on soil compaction to derive decision rules for soil protection--A case study from Switzerland. Soil and Tillage Research 92(1-2):129-143.
Tzilivakis J, Lewis KA and Williamson AR. 2005. A prototype framework for assessing risks to soil functions. Environmental Impact Assessment Review 25(2):181-195.
USDA-NRCS. 2007. Soil Quality Concepts. United States Department of Agriculture-Natural Resource Conservation Service.
Van den Akker JJH, Arvidsson J and Horn R. 2003. Introduction to the special issue on experiences with the impact and prevention of subsoil compaction in the European Union. Soil and Tillage Research 73(1-2):1-8.
van Ouwerkerk C and Soane BD. 1995. ISTRO Workshop on 'The Effects of Soil Compaction on Physical, Chemical and Biological Factors in the Environment', 25 August 1993, Melitopol, Ukraine. Soil and Tillage Research 35(1-2):1-4.

Vanapalli SK, Fredlund DG and Pufahl DE. 1996. The Relationship between the Soil-Water Characteristic Curve and the Unsaturated Shear Strength of a Compacted Glacial Till. Geotechnical Testing Journal, GTJODJ 19(3):259-268.
Vanapalli SK, Fredlund DG and Pufahl DE. 1999. The influence of Soil Structure and Stress History on the soil-water characteristics of a compacted till. Géotechnique 49(2):143-159.
Vanapalli SK, Fredlund DG and Pufahl DE. 2001. Discussion of "Influence of soil structure and stress history on the soil water characteristics of a compacted till". Géotechnique 50(00):4.
Van-Camp L, Bujarrabal B, Gentile A-R, Jones RJA, Montanarella L, Olazabal C and Selvaradjou S-K. 2004. Reports of the Technical Working Groups Established under the Thematic Strategy for Soil Protection.: Office for Official Publications of the European Communities.
VandenBygaart AJ and Angers DA. 2006. Towards accurate measurements of soil organic carbon stock change in agroecosystems. Canadian Journal of Soil Science 86(3):465-471.
Voorhees WB, Nelson WW and Randall GW. 1986. Extent and Persistence of Subsoil Compaction Caused by Heavy Axle Loads. Soil Science Society of America Journal 50:428-433.
Ward RMRCB. 1973. Soil Compaction and Recreational Use. The Professional Geographer 25(4):369-372.
West, TO, and WM Post. 2002. Soil organic carbon sequestration rates by tillage and crop rotation: a global data analysis. Soil Science Society of America Journal 66:1930-1946.
West, TO et al. 2004. Carbon Management Response Curves: Estimates of Temporal Soil Carbon Dynamics. Environmental Management Vol. 33, No. 4, pp. 507–518. Springer-Verlag New York, NY. DOI: 10.1007/s00267-003-9108-3.
Whalley WR, Dumitru E and Dexter AR. 1995. Biological effects of soil compaction. Soil and Tillage Research 35(1-2):53-68.
Wright FS, Powell NL and Ross BB. 1984. Underrow Ripping and Irrigation Effects on Corn Yield. Transactions of the ASAE 27:973-975.
Zhou J and Yu J-l. 2005. Influences affecting the soil-water characteristic curve. Journal of Zhejiang University SCIENCE 6A(8):797-804.