Most of these soils are excessively drained. The available water capacity is very low, 2 to 3 inches. Supplemental irrigation is essential for consistent crop production. The tilth of these soils is generally good to loose. They can be worked at almost any time following a rain and are commonly used for producing fresh-market vegetable crops.

They require small, but regular, additions of lime. The fertility needs are great. The soils usually supply less than 50 pounds per acre of available nitrogen. Leaching of fertilizer nitrogen and potassium is a problem, and additional fertilizer nitrogen and potash should be added to the irrigated soils. The nitrogen should be applied as sidedress applications to reduce leaching losses.

Without irrigation these soils have low yields, generally less than 100 bushels of corn and 5 tons of alfalfa per acre.

Examples of the excessively to well-drained soils include Alton, Colonie, Colosse, Colton, Hinckley, and Windsor.

The moderately well-drained soils include Claverack and Elmwood.

The somewhat poorly and poorly drained soils include Granby, Junius, and Swanton.

Other Areas

Organic or muck lands. Muck is formed by deposits of decaying organic matter in bogs. Muck lands must be drained before they can be used for agriculture. Water management is very important not only for drainage for crop production but also for irrigation and control of the rate of decay of the organic matter.

Muck soils are usually high in nitrogen but low in phosphorus, potassium, copper, and magnesium. The deep mucks may be very acidic, but shallow mucks may have marl mixed with or very close to the surface.

The muck soils are generally used for vegetable crops, but field crops are sometimes grown. When used for field crops, they should be fertilized with phosphorus and potassium (as indicated in Tables 19, 31, 40, and 50 for Soil Management Group IV), but nitrogen application rates should be reduced to one-third to one-half of the rates listed in the tables.

Nonagricultural land. These areas include urban areas, lakes, the Adirondack Mountains, rock land, and Tug Hill. A small percentage of agricultural land is located within these areas. Such lands are too small and too diverse to develop specific guidelines. Persons desiring information should contact their Cornell Cooperative Extension office.

Soil Health

In the context of crop production, the health of a soil relates to its ability to produce high quantities of good-quality crops, be resilient against weather extremes, and minimize negative environmental impacts. Functionally, it means that the soil can supply adequate amounts of nutrients but does not contain excessive levels, has appropriate pH levels, has high moisture availability, is well aerated, is penetrable to roots, has low erosion and runoff potential, and is biologically balanced. A soil's health is affected by inherent soil factors, such as texture, and management-related factors, such as fertility levels, compaction, and past erosion. Soil health may be assessed using various indicators, including soil test values, texture, penetrometer readings, erosion, and runoff.

Good aggregation, or *structure*, is an important soil health characteristic. Aggregation in the surface soil is favored by organic matter, surface residue, and an absence of erosion and forces that cause compaction. A continuous supply of organic matter provides food for a variety of soil organisms. Large pieces of fresh organic material are used by macroorganisms such as spiders and termites that will pulverize the substrate and make it available for use by microorganisms. In the breakdown of the organic materials, substances are derived that can glue soil particles into aggregates. These organic compounds, mostly *polysaccharides*, are then used by other organisms and will be decomposed over time. Therefore, a continuous supply of fresh organic materials and roots of living plants as well as healthy and diverse soil organisms are needed to maintain good soil aggregation.

Surface cover protects the soil from wind and raindrops and moderates the temperature and moisture extremes at the soil surface. An unprotected soil may reach very high soil temperatures at the surface and may become very dry. This creates a "dead zone" near the soil surface, which leads mobile organisms such as worms and insects to move deeper into the soil; small microorganisms, such as bacteria and fungi that live in thin layers of water, will die or become inactive. As a result, the natural processes of organic matter cycling are slowed. Large and small organisms function better in a soil that is well protected by crop residue cover, a mulch, or a sod, and this helps maintain good soil aggregation.

For a more extensive discussion on soil management for improved health, we recommend the book *Building Soils for Better Crops* by Fred Magdoff and Harold van Es (available from Sustainable Agriculture Publications, University of Vermont, 802-656-0484 or e-mail nesare@200.uvm.edu).

Runoff and Soil Erosion

Soil erosion degrades soils and at the same time causes flooding, sedimentation, and chemical contamination in downstream or downwind areas. Erosion results from exposing the soil directly to the destructive energy of raindrops and wind. In terms of soil degradation, the primary concern is that the best soil material, the surface layer, is being removed by erosion. Erosion also selectively removes the more easily transported finer soil particles. Severely eroded soils become low in organic matter and have less favorable physical properties, leading to a reduced ability to sustain crops and increased potential for harmful environmental impacts.

Erosion also affects the environment beyond the farm. When soil is removed, the coarser soil particles settle out first, often still within the field itself, while smaller particles may reach streams and flow into lakes and estuaries, causing a multitude of costly environmental problems. These include siltation of streams, lakes, estuaries, and reservoirs; upsetting aquatic ecosystems; reducing recreational opportunities; and shortening the life span of dams. In addition, the sediment contains other chemicals of environmental concern such as nitrogen, phosphorus, pesticides, and pathogens. Phosphorus is the primary concern for nutrient enrichment for most of New York's freshwater lakes, whereas nitrogen is the main problem in coastal estuaries. Pathogens are the principal concern in drinking water supplies such as the reservoirs for New York City and Syracuse. Runoff and erosion from agricultural lands, especially when manured, remain the most serious nonpoint source pollution problem in New York.

A complicating dimension of erosion is that it is ephemeral, and it is most severe during relatively few weather and climate extremes. Thirty to forty percent of the water erosion that might occur on a particular field in a 30-year period may be the result of a single extreme rainfall event. In New York, we are particularly concerned about rainfall on frozen soils because virtually all the precipitation runs off. One may not fully recognize the erosion potential and put short-term interests above good land stewardship.

Tillage Erosion

The process of tillage and its interaction with the gravitational force can result in much movement of soil in a field. Soil is thrown further downslope when tilling in the downslope direction than uphill when tilling in the upslope direction (Fig. 4a). Downslope tillage typically occurs at greater speed than when traveling uphill, making the situation worse. Tillage along the contour also results in movement of soil downslope because soil that is lifted up by a tillage tool will fall down at a slightly lower position than that from which it came (Fig. 4b). A more serious situation may occur when using a moldboard plow along the contour with the furrow thrown down the slope to obtain better inversion than trying to turn the furrow up the slope (Fig. 4c). Tillage erosion causes soil loss from the upper slopes to the swales and is especially detrimental in complex, undulating topographies. Localized soil losses from upper slopes may exceed 50 tons per acre, often greater than those from water or wind. On the other hand, tillage erosion does not result in off-site damage because the soil is merely moved from higher to lower positions within a field.

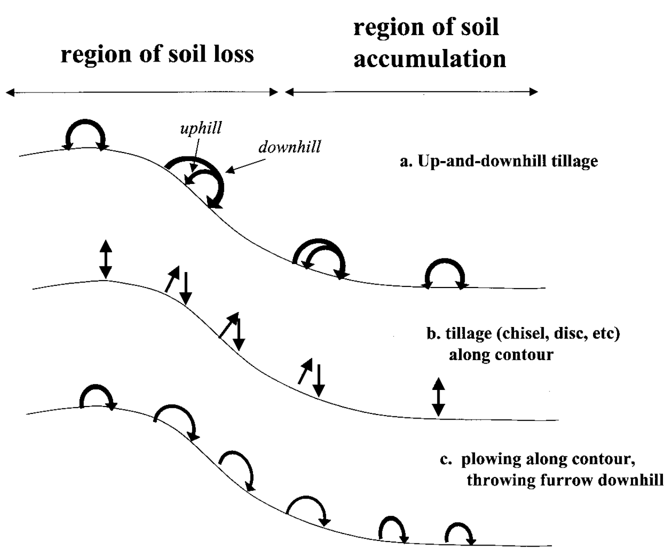

Fig. 4. Causes of tillage erosion

Solving Erosion Problems

Although effective erosion control is possible without seriously compromising crop productivity, it is not always easy because it may require considerable investment and good management skills. Agronomic measures that increase soil surface protection and decrease soil disturbance, including reduced tillage, no/zone-tillage, cover cropping, and rotations with perennial crops, are the preferred ways of addressing erosion concerns.

Reduced-tillage or **no-tillage** systems have been sufficiently refined to be successful in many cropping systems by providing similar or even better economic returns while providing excellent erosion control. The maintenance of residues on the soil surface and the lack of soil loosening by tillage greatly reduce the effects of the energetic impact of raindrops and the hydraulic shear of runoff waters. Soil losses decrease dramatically with moderate amounts of surface residue (Fig. 5). Therefore, tillage systems that leave 30 percent or more surface cover are considered to be soil conserving. The effects of wind shear are also greatly

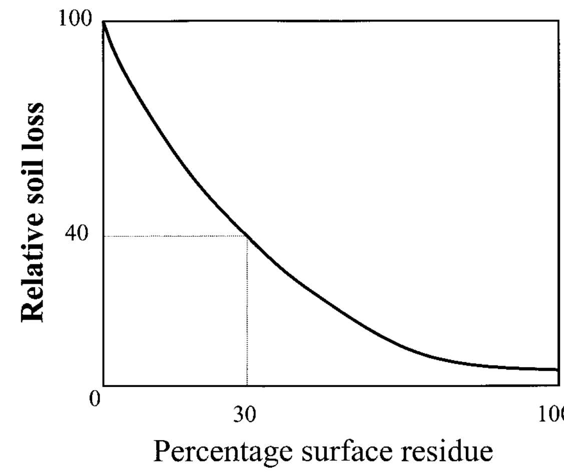

Fig. 5. Soil erosion reduction with increased surface residue level

reduced by leaving crop stubbles on untilled soil and anchoring the soil with roots. Reducing tillage intensity also slows down the loss of soil organic matter and aggregation under intensively tilled systems and thereby promotes higher infiltration rates and lower runoff and erosion. Leaving a rougher soil surface by eliminating secondary tillage passes and packers that crush natural soil aggregates may significantly reduce runoff and erosion losses by preventing surface sealing during intensive rains. Reducing or eliminating tillage also diminishes tillage erosion and keeps soil from being translocated down the hill. Transition to tillage systems that increase surface cover is probably the single most effective and economic approach to reducing erosion.

Cover crops help reduce erosion in several ways. Either in active or dormant state, they provide surface cover and protect the soil surface, often at times when the soil is very susceptible to erosion. The roots also hold soil in place against shear forces from the runoff water and wind. Cover crops improve soil aggregation and infiltration capacity, thereby further reducing the potential for runoff and erosion. They are especially effective in reducing erosion if they are cut and mulched rather than incorporated. The use of cover crops in New York is severely limited by the short growing season. Winter rye is generally the only cover crop that can be reliably grown during late fall and early spring when corn and soybean are the primary crops. The benefits of cover crops for the purpose of erosion reduction are minimal when high-residue tillage systems are used and primary tillage occurs in the spring.

Perennial crops that are rotated with annual crops provide longer-term soil cover and build soil aggregation, resulting in a decrease in soil erosion. In effect, the degradational effects of the annual crops are in part offset by the sod crops, thereby decreasing the average annual erosion rate. Ideally, such rotations are combined with reduced and no-tillage practices for the annual crops.

Adding **organic matter** such as manure, compost, or sludge materials (see also "Land Application of Sludges") improves soil aggregation, increases infiltration, and reduces runoff and erosion. A continuous supply of organic matter results in more stable aggregates that better resist raindrop impact and thereby reduces the potential for slaking (aggregates falling apart) and surface sealing. Fresh organic matter also increases biological activity, especially by earthworms that create channels for water infiltration.

Addition of organic matter may, however, have an indirect negative effect on erosion in that the amendments need to be incorporated effectively into the soil. The adoption rate for no-tillage practices is thus lower for livestock-based farms than for grain farms. Direct injection of liquid organic materials in a zone or no-till system is generally an option but requires additional equipment investments.

Other soil conservation practices are available and their applicability depends on the soil, climate, and cropping system used on the farm. Grassed waterways are widely used to reduce scouring in the swales where runoff water concentrates, but they do not reduce erosion in other areas of the field. Developing alternating strips of row and sod crops along the contour, referred to as strip cropping, is an effective way of reducing erosion losses. In this system, erosion from the row crop is not allowed to aggravate over long unprotected slopes as the soil is protected when the runoff water reaches the sod crop, and possible sediments from the row-crop strip are immediately filtered out. This conservation system is generally attractive in fields that have moderate erosion potential and on farms with uses for both row and sod crops (e.g., dairy farms).

Wind Erosion

Wind erosion is a localized problem in New York, notably on mucks. Besides causing soil losses, this erosion may lead to serious air quality problems in downwind areas, which is especially of concern near densely populated areas. Reduced and no-tillage, cover cropping, and perennial rotation crops reduce wind erosion by anchoring soil materials. In addition, practices that increase the roughness of the soil surface diminish the effects of wind erosion. The resulting increase in turbulent air movement near the land surface reduces the wind shear and its ability to sweep up soil material. Therefore, fields subjected to this erosion may also be rough-tilled. In addition, tree shelter belts planted at regular spatial intervals perpendicular to the main wind direction effectively act as windbreaks and reduce erosion losses.

Soil Compaction

Soil compaction is a significant yield-limiting factor in New York that has various causes and effects on crop performance. We recognize three types of soil compaction (Fig. 6).

Crusting and surface sealing can occur when a soil is unprotected by surface residue or a plant canopy and the energy of the raindrops disperses the wet soil aggregates and pounds them together into a thin but dense surface layer. They are easy to detect visually by the condition of the soil surface after heavy rains in the early growing season, especially with clean-tilled soil.

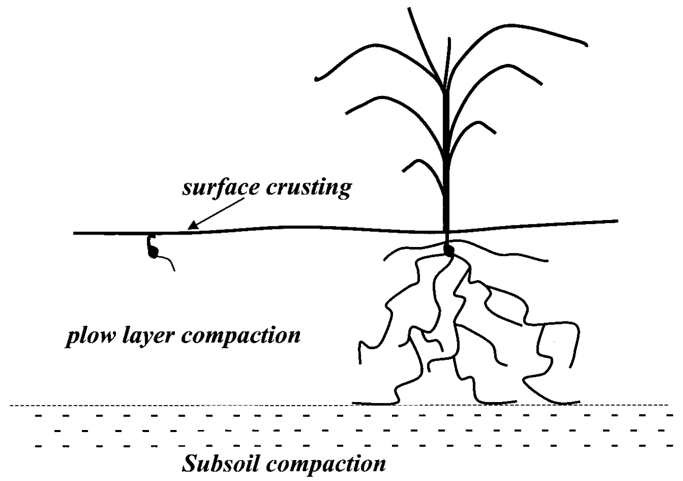

Fig. 6. Three types of soil compaction and their effects on crop growth

The agronomic impact of surface crusting is most pronounced when heavy rains occur before seedling emergence. The plant's inability to protrude through the hard surface delays growth until the crust mellows with the next rains. If such showers do not occur for awhile, the crop may be set back considerably. A second consequence of crusting and sealing of the soil surface is the reduced water infiltration capacity. This increases the runoff and erosion potential and diverts precipitation that otherwise would be available to plants.

Crusting is a symptom of weak soil structure that becomes pronounced with intensively and clean-tilled soils, especially when aggregates were pulverized. If fields experience this problem, the best approach is to reduce tillage intensity and use systems that leave residue or mulch on the surface. Even residue coverages as low as 30 percent will greatly reduce crusting and provide important pathways for water entry. Crusting is also reduced through practices that improve soil structure such as reduced tillage, cover cropping, rotations with perennial crops, and adding organic materials. For a short-term solution, early-season soil crusts may be broken up with a rotary hoe or light tooth harrowing.

Plow layer compaction has probably occurred to some extent in all intensively worked agricultural soils in New York. Such compaction is caused by erosion, organic matter imbalances (burning of organic matter through tillage and insufficient return of fresh organic materials), and the compactive forces exerted by field equipment and tillage implements.

Compaction of soils by heavy equipment and tillage tools is especially damaging when soils are wet. At higher water contents, soil can be easily molded and is said to be *plastic*. It will be seriously compacted by traffic or if tilled because the soil aggregates flow together into a smeared, dense mass. This can be expressed as deep tire ruts in a field or smeared cloddy furrows after tillage. Dryer soils are *friable*. Aggregates will resist compaction and only break apart rather than mold under pressure. This is why the potential for compaction is so strongly influenced by the timing of field operations relative to a soil's consistency.

A soil's consistency state is strongly affected by its texture (Fig. 7). For example, as coarse-textured sandy soils drain they rapidly change from being plastic to friable. Fine-textured loams and clays, however, need longer drying periods to change from being plastic, and this delays field operations. To be sure that a soil is below the Plastic Limit, you can do the simple "ball test" by taking a handful of soil from the lower part of the plow layer and trying to squeeze it into a ball. If it molds easily and sticks together, the soil is too wet. If it crumbles, it is sufficiently dry for tillage or traffic.

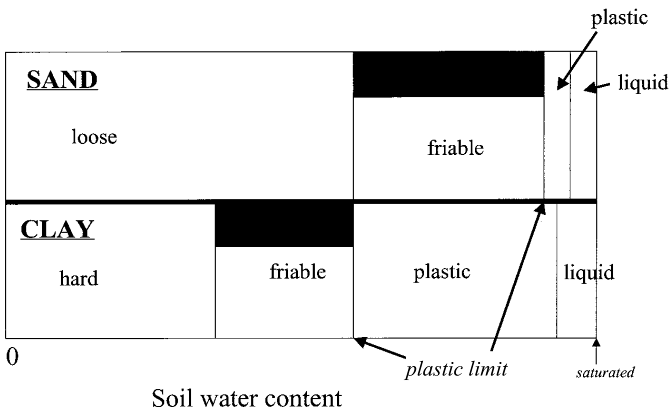

Fig. 7. Soil consistency states as affected by soil water content for a sand and a clay soil. Shaded areas indicate optimal wetness ranges for tillage.

Compaction of the subsoil, the soil below the surface layer that is not normally tilled, is usually called a "plow pan," although it is generally caused by more than plowing alone. The subsoil can be become compacted because it is usually wetter, naturally denser, higher in clay content, lower in organic matter content, and less aggregated than the plow layer. In addition, the subsoil is not loosened by regular tillage and cannot easily be amended with additions of organic materials, so its compaction is more difficult to manage.

Subsoil compaction may be the result of direct loading by the force of a tillage implement, especially a plow or disk, in contact with the subsoil. It also occurs when a field is moldboard plowed and a set of tractor wheels is placed in the open furrow, thereby directly compacting the soil below the plow layer. Subsoil compaction also occurs when heavy vehicles with poor weight distribution are used. The load exerted on the surface is transferred into the soil along a cone-shaped pattern (Fig. 8). With increasing depth, the force of compaction is distributed over a larger area, thereby reducing the pressure. When the loading force at the surface is small, say through foot traffic or a light tractor, then the pressures exerted below the plow layer are minimal. But when the load is high, the pressures at depth are still sufficient to cause considerable soil compaction. And when the soil is wet, the downward transfer of the forces of compaction is greater and the soil is more susceptible to harm. As a rule of thumb, axle load in excess of 7 tons on wet soils will already do considerable subsoil compaction damage. Combines, loaded farm trucks, and heavy spreaders can therefore do considerable damage to the subsoil if they are used on wet soils.

Effects of Soil Compaction on Crops

Compaction causes a soil to lose aggregation and a fraction of its larger pores. It is particularly harmful for fine and medium-

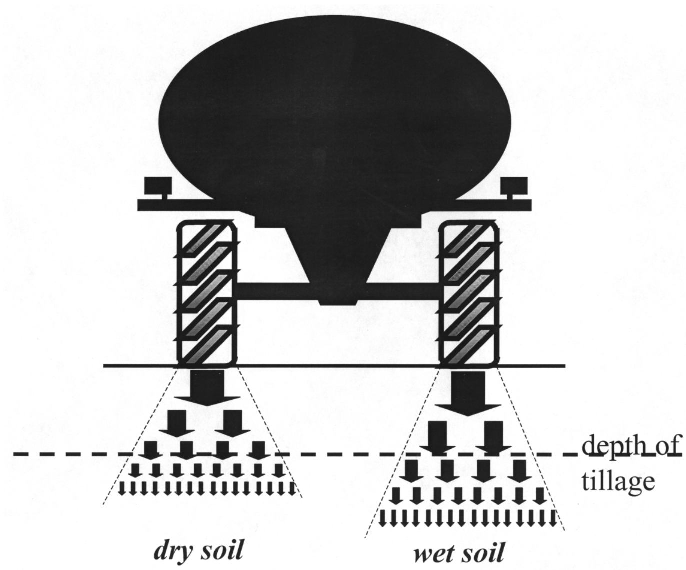

Fig. 8. Transfer of heavy loads from the soil surface into the subsoil for dry and wet soils

textured soils that depend on aggregates for good infiltration and percolation of water as well as air exchange with the atmosphere. Compacted soil becomes hard upon drying and can restrict root growth and the activity of soil organisms. Figure 9 depicts the relationship between soil water content and soil strength for a well-structured and a compacted soil: as the soil

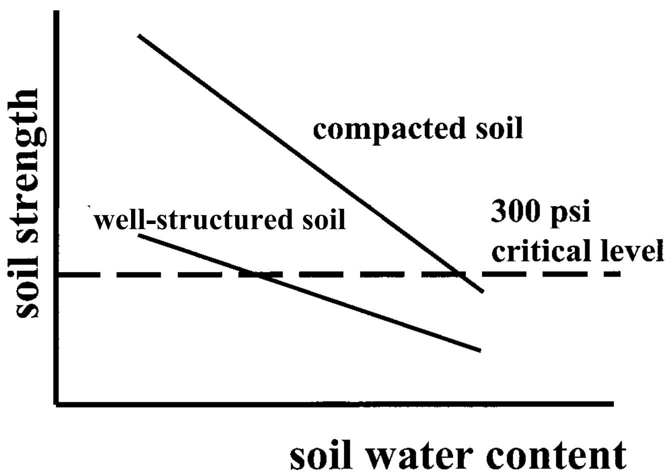

Fig. 9. The effect of soil wetness on soil strength (hardness) for a well-structured and a compacted soil

dries, it becomes harder. For a well-structured soil, soil strength at high water contents is well below the critical level of 300 psi, the hardness at which root growth ceases for most crops. As the soil dries, it becomes harder but may not exceed the critical level for most (or all) of the wetness range. A compacted soil, however, is harder in the wet range, where it may even be above the critical level, depending on its severity. And when it dries, a compacted soil hardens quicker than a well-structured soil and may reach well above the 300 psi level. Thus a compacted soil has a very narrow water content range for good root growth.

In addition, actively growing roots need pores greater than about 0.005 inch (0.1 mm), the size of most root tips, to be able to anchor themselves into a soil pore before they can protrude and grow outwardly. Compacted soils that have few or no large pores will therefore not allow plants to be effectively rooted, limiting water and nutrient uptake.

A root system in a compacted soil has large, thick roots and only a few fine ones or root hairs (Fig. 6). The thick roots are able to find some weak zones in the soil, often by following crooked patterns. But they have thickened tissue and cannot take up water and nutrients efficiently. In many cases, roots in degraded soils do not reach beyond the tilled layer into the subsoil, it is just too dense and hard for them to grow. Deeper root penetration is often critical under rainfed agriculture, and subsoil compaction therefore increases the probability of yield losses from drought stress.

While reduced root growth limits the volume of the soil that is used for water and nutrient supply, it also has a direct effect on plant growth. A root system that is up against mechanical barriers sends a chemical signal to the plant shoot, resulting in a slowdown and stunting of growth.

Compacted soils also experience problems under wet conditions. A poorly structured plow layer has few large pores that drain readily and allow for air exchange. Even if the soil has been loosened by tillage, it will settle into a dense mass after a few rains. If soil wetness persists, the lack of aeration will generate anaerobic conditions, causing reduced crop growth and denitrification, especially in areas that are imperfectly drained. Poorly structured soils can easily lose 50 lb. per acre of nitrogen during wet soil conditions in the late spring.

In general, it is important to recognize that soil compaction creates problems for crops under both wet and dry soil conditions. Compacted soils have a narrow water range under which crops can grow well and problems are therefore more expressed under extreme weather conditions.

Diagnosing Plow Layer and Subsoil Compaction

These types of compaction can be evaluated with a spade or soil penetrometer. The latter is a tool that measures the resistance to soil penetration as measured by pushing a rod with a cone-shaped tip into the soil. When penetration resistance is greater than about 300 psi, the soil may be too hard for root penetration. Remember that the strength of the soil depends on the water content (Fig. 9), and it is best to repeat penetrometer measurements several times during the period of active root growth to make a good assessment. Moreover, penetrometer measurements in recently tilled soil may not be representative of soil hardness later in the season when the soil has settled after several rains. It may be useful to make penetrometer measurements at the beginning of the growing season to evaluate the needs for tillage. If readings at that time are near or above 300 psi, they will surely be higher when the soil dries out later in the season. When making penetrometer measurements, take separate notice of soil strength in the plow layer and that in the subsoil, as the remedial action may be different for each case.

When using a penetrometer, keep in mind that soil strength is extremely variable and multiple penetrations should be made and averaged before drawing conclusions. Headlands also receive greater compaction and they are not representative of the whole field. Penetrometers do not work well in rocky soils because the measurement is not valid when the tip hits a rock. In addition, the devices are not very effective at predicting rooting behavior in structured clay soils. They may harden upon drying but still have macropores that allow roots to proliferate.

A spade can be used to visually evaluate soil structure and rooting. This is best done when the crop is in an early stage of development but after the rooting system had a chance to get established. Compacted soil is hard and will dig up in large clumps rather than granules. Roots in a compacted plow layer are generally stubby and have few laterals and root hairs (Fig. 6). They also often follow crooked paths as they try to find zones of weakness. Rooting density below the plow layer is an indicator of subsoil compaction. Soils that have severe *plow pans* will show a virtual absence of roots in the subsoil and often have roots that move horizontally above the pan. Keep in mind that some crops such as grasses are naturally shallow rooted and may not necessarily experience subsoil compaction problems.

Compaction may also be recognized by observing crop growth. A compacted soil experiences greater nitrogen losses from denitrification, resulting in leaf yellowing. Hardsetting occurs on compacted soils, untilled or tilled, after thorough wetting and subsequent drying. The crop may consequently experience a noticeable period of stunted growth.

Compaction can also reveal itself through greater pest problems. As soil compaction generally reduces growth, it also affects the crop's ability to fight or compete with pathogens, insects, and weeds. These pest problems may therefore become more apparent simply because the crop is weakened. For example, compacted soils that are carelessly put into a no-till system may show greater weed pressure because the crop is unable to compete effectively. In addition, dense soils that are poorly aerated are more susceptible to infestations of certain soil-borne pathogens such as *Phytophthora* during wet periods.

Addressing Soil Compaction Problems

Preventing or abating soil compaction is challenging and rarely gives immediate results. It generally requires a comprehensive, long-term approach to addressing soil health issues. Compaction on any particular field may have multiple causes and the solutions are often dependent on the soil type, climate, and cropping system.

Drainage

Lands that are imperfectly drained often have more severe compaction problems than those that drain adequately because it may be difficult to prevent traffic or tillage under wet conditions. Improving drainage may go a long way toward preventing and reducing compaction problems on those soils. Subsurface (tile) drainage helps dry the subsoil and thereby reduce compaction in deeper layers.

Clay soils often pose the greatest challenge because they remain in the plastic state for extended periods in the spring. They are also self-mulching: Once the top inch near the soil surface has dried out, it becomes a barrier to further evaporative losses. This keeps the soil below in a plastic state for extended time periods, thereby preventing the soil from being worked or trafficked without causing excessive smearing and compaction damage. Those soils are therefore often fall tilled because they are then generally dryer. Another approach is to use cover crops to dry the soil in the spring. Their roots will effectively pump water from the layers below the soil surface and allow the soil to make the transition from the plastic to the friable state before spring tillage. Because these soils have high moisture-holding capacity, the concern about water losses to the following crop are generally minor.

Tillage as a Problem and a Solution

Tillage plays a paradoxical role in that it *causes* as well as *eases* problems with soil compaction. Repeated intensive tillage oxidizes organic matter, reduces soil aggregation, and compacts the soil over the long term. It also causes erosion and the loss of topsoil and may form plow pans. On the other hand, tillage relieves soil compaction by loosening the soil and creating pathways for air and water movement and root growth. This relief, as effective as it may be, is temporary and tillage will need to be repeated in the next growing seasons. In fact, tillage intensity often increases over time to offset the problems of cloddyness associated with compaction of the plow layer.

The solution to this problem is not necessarily the cessation of tillage altogether. In a sense, compacted soils have often become "addicted" to tillage, and going abruptly to a no-till system will often result in failure. Practices such as zone building and paraplowing that perform some soil loosening with minor disturbance at the soil surface help in the transition from a tilled to an untilled system. Another approach is the gradual reduction in tillage intensity through the use of tillage tools that leave residue on the surface (e.g., chisel tillage) and a good planter that ensures good seed placement in a soil that received minimal secondary tillage. Such a system will reduce organic matter losses and erosion in the long run.

Deep Tillage

Deep tillage (subsoiling) is a method used to alleviate compaction below the depth of normal tillage (see also p. 21). It is often erroneously seen as a cure for all types of soil compaction, including plow layer compaction. It is a rather costly and energy-consuming practice that should not be performed regularly. Practices such as "zone building" also loosen the soil below the plow layer but do not loosen the soil full-width and keep residue on the surface. Deep tillage may be beneficial on soils that have developed a plow pan. Simply shattering this pan allows for deeper root exploration. For deep tillage to be effective, it needs to be performed when the entire depth of tillage is sufficiently dry and in the friable state. It is therefore typically best done in the fall, especially for finer-textured soils. The practice tends to be more effective on coarse-textured soils (sands, gravels) because they often develop a distinct (2 to 4 inches thick) pan width under the plow layer. Fine-textured soils are often hard in the entire subsoil and the beneficial effects of deep tillage are then less pronounced. After performing deep tillage, it is important to prevent future recompaction of the soil by heavy loads and plows.

Working and Loading the Soil

Compaction of the plow layer or subsoil is often the result of working or trafficking the land when it is too wet. The first step in addressing compaction is to do a critical evaluation of all traffic and practices that occur on a field during the year and determine which field operations are likely to be most damaging. The main criteria in this should be

1. the soil moisture condition under which the traffic occurs.
2. the relative compactive effort of the field traffic, i.e., equipment weight and load distribution.

This allows for evaluation of the practices that cause the greatest compaction damage and helps focus the evaluation of alternatives. For example, with a late-planted crop, soil conditions during tillage and planting may generally be dry and minimal compaction damage occurs. Similarly, mid-season cultivations will do little damage because conditions may be dry and the equipment tends to be light. If that crop is often harvested under wet conditions, heavy harvesting equipment and uncontrolled traffic by trucks that transport the crop off the field will do considerable compaction damage. In this scenario, the emphasis should be placed on improving the harvesting operation as most compaction damage occurs during that time. In another scenario, a high-plasticity clay loam soil that is often spring plowed when still too wet, much of the compaction damage may occur at that time, and alternative approaches to tillage should be a priority.

Distributing Loads

Improving the design of field equipment may help reduce compaction problems by better distributing the vehicle's load. Assuming a fixed total vehicle weight, the best approach to spreading the compactive load is through the use of tracks, which will especially reduce the potential for subsoil compaction. Tracked vehicles may provide a temptation to traffic the land when it is still too wet as they have better flotation and traction, which may still result in smearing under the tracks.

Use of multiple axles reduces the load on tires. Even though the soil receives more tire passes, the resulting compaction is significantly reduced, thereby especially reducing compaction of the subsoil. Use of dual wheels similarly reduces compaction by increasing the footprint, although this is less effective for reducing subsoil compaction as the pressure cones (Fig. 8) merge at depth. Dual wheels are very effective in increasing traction but are not recommended on tractors performing seeding or planting operations because they compact crop rows on both sides. This is a concern with small planters but has less negative impact with large ones.

Compaction in the plow layer is also related to the contact pressure of the tire, whereas compaction in the subsoil is more related to total axle loads. The contact pressure is defined as the pounds per square inch of pressure exerted by the tire on the soil and is roughly equivalent to the tire inflation pressure. As a rule of thumb, by cutting the tire inflation by half you will double the size of the tire "footprint."

Cover and Rotation Crops

Cover and rotation crops can significantly help alleviate soil compaction. The choice of cover/rotation crop should be defined by the climate, cropping system, nutrient needs, and also by the type of soil compaction. Often perennial crops have active root growth early in the growing season and can protrude into the compacted layers when they are still wet and relatively soft. Grasses generally have shallow, dense fibrous root systems that have a very beneficial effect on the surface layer but do not ameliorate the subsoil. Crops with deep taproots, such as alfalfa, have fewer roots at the surface but can protrude into a compacted subsoil. In many cases, a combination of cover crops with shallow and deep rooting systems is preferred. Ideally, such crops are part of the cropping system by functioning as a rotation crop.

The relative benefits of incorporating or mulching a cover crop are site-specific. Incorporation through tillage will loosen the soil, which may be beneficial if the soil has been heavily trafficked. This would be the case with a sod crop that has been actively managed for forage production, sometimes with traffic under relatively wet conditions. This practice also provides for rapid nitrogen mineralization. Cutting and mulching, on the other hand, does not loosen the soil and reduces nutrient availability, but is advantageous by providing a heavy protective mat at the soil surface. A few innovative farmers have successfully adopted cut-and-mulch systems involving cover/rotation crops such as rye, hairy vetch, or sorghum-sudangrass. They appear to perform well during dry years, especially on medium to coarse-textured soils. Slugs may cause problems in wet years.

Addition of Organic Materials

Adding animal manure, compost, or sewage sludge benefits the surface layer in which they are incorporated by providing a source of organic matter. The benefits relative to soil compaction, however, may be mixed because the spreaders themselves are also often a major cause of compaction. The need for incorporation of animal manure is also often a barrier to the adoption of no-till or zone-till systems. This problem can be overcome only through an additional investment in manure injection tools. In general, organic materials should be added with care so as to receive the biochemical benefits while not aggravating compaction problems.

Controlled Traffic

In conventional tillage corn systems, it has been estimated that as much as 80 percent of the soil surface will be tracked in a season, with some areas receiving several wheel passes. One of the most promising but rarely adopted practices for reducing soil compaction is the use of controlled traffic lanes. The compaction is confined to designated zones between the rows. The firm, compacted areas also offer greater bearing capacity to support machinery. This system is most easily adopted with row crops in zone, ridge, or no-till systems where crop rows and traffic lanes remain recognizable year after year. Ridge tillage in fact dictates controlled traffic since wheels cannot cross the ridges. Zone and no-till do not necessarily require controlled traffic but greatly benefit from it because the soil is not regularly decompacted through rigorous tillage. Adoption of controlled traffic lanes typically requires some adjustment of field equipment to ensure that much of the wheel traffic occurs in the same lanes, and it also demands considerable discipline from the equipment operators. For hauling equipment, such as trucks taking harvested materials off the field, predefined access roads limit the extent of compaction damage.

Tillage

New technologies have changed the need for tillage. Chemical herbicides have reduced the need for tillage as a weed control method, and new planters and drills allow for better seed placement without the prior preparation of a full-width seedbed. On the other hand, increased mechanization, intensive tillage, and erosion have degraded many agricultural soils to an extent where they are thought to require tillage to provide temporary relief from compaction. Indeed, many New York soils are now primarily tilled for compaction relief and incorporation of amendments rather than for the traditional purposes of weed control and seedbed preparation. Many of our lands can now be managed with limited tillage to produce a crop with the same economic return as conventional tillage systems. It remains a challenge, however, to manage the soil in the right manner to make reduced tillage systems successful. Practices that increase soil quality, such as crop rotation and manure application, also increase the success of reduced tillage.

Full-Width Primary Tillage Systems

A full-width system manages the soil evenly across the entire soil surface. It typically involves a primary tillage pass to loosen the soil and incorporate materials at the surface (e.g., amendments, weeds), followed by one or more secondary tillage passes to create a suitable seedbed. Primary tillage tools are generally moldboard plows, chisels, and disks, while secondary tillage tools may include tools such as disk harrows, rollers, packers, and drags. These tillage systems create a uniform and often finely aggregated seedbed.

Moldboard plowing, often called conventional tillage, cuts, lifts, and inverts the top 6 to 12 inches of soil and buries essentially all surface residues. The horsepower requirement is 15 to 20 HP per moldboard. Moldboard plowing provides effective and homogeneous loosening of the root zone and facilitates soil warming compared to undisturbed, residue-covered soils. It is effective at incorporating amendments and turning under sods and weeds. It is generally successful and will almost always facilitate a decent crop.

Moldboard plowing has several negative features including high power and energy requirements and the need for multiple secondary tillage trips to prepare a seedbed. Compaction damage at the bottom of the plow zone can result from the pressures of the plow itself as well as the compactive loads of wheels of the tractor running in the open furrow. Larger, on-land equipment allows for the tractor to drive on unplowed land and reduce this subsoil or “plow sole” compaction. From an environmental perspective, moldboard plow systems have high erosion potentials and cause high organic matter oxidation rates and long-term soil degradation. They also generate tillage erosion on sloped lands if the furrow is cast downhill along the contour or the field is plowed up and down the slope.

An optional clodbuster bar attached behind the plow breaks up large clods before they dry out and become hard and also helps to level the soil and eliminate large air voids. The extra surface pulverization done by the clodbuster would seldom be recommended for fall plowing as a rougher surface would be more desirable going into the winter.

Chisel tillage involves a set of shanks being pulled to loosen but not invert the soil. Chisel implements require less power (10–15 hp per shank) and energy than moldboard plows and they can be used at higher traveling speeds. The result is a rough surface that has much of the original residue cover, thereby reducing erosion rates compared to plowed ground. Some recently developed chisel tools allow for soil loosening with minimal incorporation of surface residue and no need for secondary tillage. Chisels also allow for more flexibility in depth of tillage, generally from 5 to 12 inches (deeper with special shanks), although research done in central New York showed no benefit from increasing tillage depth beyond 9 inches. Increasing operating speed and depth results in less residue cover. Soil cover percentage after chisel tillage can range from 40 percent using 3- to 4-inch wide twisted shovels to 80 percent using sweeps or straight narrow points. Disks or coulters mounted on the front frame of the chisel help to chop residues and prevent debris from building up and clogging the shanks. Chisel tillage generally yields slightly lower than moldboard plowing, especially with heavier and compacted soils. However, it is often offset by lower costs and significantly reduced erosion potential.

Secondary Tillage

The objective of secondary tillage is to prepare a seed zone after the soil has been plowed with a primary tillage tool such as a moldboard plow or chisel plow. The large soil clods exposed by the primary tillage are broken down so that the seed zone can contain fine soil particles that supply moisture to the germinating seed. Repeated passes with finishing tools may re-compact the soil to levels equal or greater than before primary tillage. Intensive secondary tillage may in some cases be required to establish good crop stands, especially with small-seeded crops and an absence of conservation tillage planters or drills. In other cases, secondary tillage may be minimized, reducing costs in labor, fuel, and equipment, as well as the loss of soil structure. For row crops, the areas between the plant rows should be kept rough to reduce soil crusting and hardsetting.

Disking breaks up clods and smooths and firms the soil within the top 2 to 6 inches. It is mostly used as a secondary tillage tool, but heavy disks can be effective primary tillage tools on lighter soils or those that require only shallow tillage. When used as a secondary tillage tool, the disk breaks the larger clods exposed by the primary tillage operation and, by varying the speed of operation, distributes and levels the soil across the width of the implement. These implements are available in two types. Offset disks have a righthand gang followed by a lefthand gang. Tandem disks have two opposing gangs that throw soil outward, followed by two gangs that throw soil back to the center. The concave cutting blades are mounted in a gang, which can be variably offset from the direction of travel, depending on the desired level of tillage action. Depending on the setting, 30 to 70 percent of the surface residue may be incorporated. The weight of the implement typically rides entirely on the edges of these coulters, which can cause a "disk pan" when it is performed under wet soil conditions. A single or double pass of a disk breaks up clods but generally does not result in soil pulverization. Excessive use of disking, however, can result in organic matter losses, aggregate breakdown, and considerable tillage erosion.

*Spring-tooth harrows and tine cultivator*s typically have three or four ranks of equally spaced flexible spring steel shanks or tines that "comb" the surface and break up soil clods. They are typically used as a finishing tool prior to planting when a fine seedbed is needed. A single pass is often effective with primary-tilled soil that has been allowed to settle.

Packers, cultipackers, and rolling baskets crush and pulverize soil clods into a firm and smooth seedbed. These finishing tools promote organic matter oxidation and increase the potential for crusting, hardsetting, runoff, and erosion from subsequent rains.

Restricted Tillage Systems

These tillage systems build on the concept that the soil does not need to be uniformly loosened over the entire width, but the plant row and the interrow areas may be managed differently. They do not require secondary tillage.

No-tillage does not involve soil loosening except for a very narrow and shallow area immediately around the seed zone. Localized disturbance in no-till is typically accomplished with a fluted/rippled coulter on the planter or drill. These tillage systems are very effective for erosion control, and the lack of intensive tillage allows for long-term buildup of organic matter levels. No-tillage systems have proven to be very well adapted to coarse-textured soils (sands and gravels) because they tend to be softer and less susceptible to compaction. The transition from conventional tillage typically takes a few years, after which no-till may even outyield it. The quality of no-tilled soils, by almost any measure, improves over time as surface residue effectively protects the soil against erosion and increases biological activity by shielding the soil from temperature and heat extremes. The surface residue also reduces water evaporation, and no-till rooting systems tend to proliferate more into the subsoil, thereby reducing the susceptibility to drought. No-tillage may show significant yield losses on compacted soils, especially if fine-textured. Fields in no-till are planted with a single trip across the field, thereby providing considerable time and energy savings compared to tilled ground and allowing for more timely planting. No-tillage causes a change in weed problems dominated by biennials and perennials and generally requires more herbicides. Increased pest pressure owing to crop residues may require more use of insecticides, especially in continuous corn. Slugs may pose considerable problems during wet seasons. Pesticide leaching may be increased as continuous macropores allow for more rapid movement of chemicals to groundwater. In general, no-tillage systems require good management skills and continued learning and adaptation.

Zone tillage is used on row crops and recognizes the benefits of some further soil disturbance of the soil in the plant row and uses multiple fluted coulters mounted on the forward frame of the planter to develop a fine seedbed of approximately 4 x 4 inches. It also uses trash wheels to move residue away from the row, thereby improving seed placement and soil warming. The system may include a separate pass of a "zone building" implement during the off season, typically involving a narrow deep tillage shank or knife, in some cases combined with a trash remover or hilling disk, to perform in-row tillage and overcome compaction problems. Zone till typically provides a yield response of 5 to 7 percent over true no-till with the best responses on heavier, less well-drained soils with heavy residue. Zone-till yields may be similar to moldboard plowing on well-structured soils, but tend to be somewhat lower on degraded soils. A significant advantage of adoption of zone tillage is that the primary investment, a planter, can also be effectively used in combination with other tillage systems, thereby providing great management flexibility and opportunities to reduce secondary tillage.

Strip tillage is an adaptation of the zone-till planting system. A cultivator toolbar is equipped with coulters and row cleaners set up with the same spacing as the zone-till planter. This cultivator is used, usually in the fall, to clear the residue and disk up a small ridge of soil in the area that, after mellowing over the winter, will be the seedbed strip next spring. Some growers have used this operation to combine a more rigorous ridging up of soil (up to 4 inches) and an application of any needed phosphorus, potash, or both. This innovation in crop-row pre-tillage allows for the cleared area (the seed zone) to dry and warm faster the next spring. The fall window of opportunity for preparing the strips may be short depending on the soil conditions after harvest. In rough, uneven fields the strip preparation may provide for a leveling of the row area at planting, thereby increasing uniformity of seedling emergence. Experience in the Midwest has shown that strip tillage allows for earlier planting and could increase yields over conventional no-till systems.

This system has not been tested in research trials in New York but is expected to be well adapted to most of our soils.

Ridge tillage is a system of preparing ridges and furrows of soil, of which the ridges will function as the plant rows. The ridges typically require the purchase of an appropriate cultivator. The soil on the ridge benefits from its elevation by drying and warming more quickly in the spring. As in zone-till, the seed can be sown in one pass over the field in the spring. Very little soil needs to be removed from the ridge-tops for planting—even previous crop root masses can remain. Crop residue remains on the surface, thereby providing excellent erosion control. Using a zone-till planter on prepared ridges has resulted in good stand establishment and comparable yields to other tillage systems on a silt loam soil and a heavy clay soil. Timely, early-season between-row cultivation complements a reduced herbicide application banded in the row only and also rebuilds the ridge for the next season. Another option is to use two cultivations for weed control. The first cultivation loosens the soil and a second, heavy cultivation rebuilds the ridge. The ridges are maintained year to year, making the system well suited to continuous row crops. This soil management system requires controlled traffic whereby the ridges themselves do not become compacted at all. Combine wheel spacing may have to be modified to track down the furrow lanes and not on the ridges. If you are planning to rotate into ridge-till, ensure that compacted fields have been loosened with a primary or deep tillage implement to undo any root zone compaction, which will limit the performance of any reduced till system. Ridge tillage has some practical negative features: The ridges force all field traffic to follow the row direction throughout the field. In addition, ridge tillage does not fit with cereal, forage, and narrow-row grain crop production.

Deep Tillage

Deep tillage and *subsoiling* are major soil disturbance techniques that are intended to rip through the soil to break up dense subsoil soil layers (see also p. 18). The soil surface disturbance varies with the shape and geometry of the shanks. Those with winged tips provide greater lateral shattering, resulting in more even breakup of the subsoil. Deep tillage is generally best performed in the fall on medium- to fine-textured soils as they may not dry sufficiently in the spring. Subsoiling generally requires 30–60 hp per shank and costs $20–$30 per acre. The high cost of deep tillage must be weighed against yield advantages and can be justified only when subsoil compaction and plow pans are present. It does not necessarily provide full benefits if the plow layer is also compacted from intensive management.

*Zone-builder*s are deep tillage implements that use large narrow shanks spaced on a toolbar to match the row placement of the following crop. They loosen the soil mostly in the planting zone with minimal surface disturbance or incorporation of residues. A zone-till planter subsequently levels the soil and plants in one pass right on the deep tilled zone. Zone builders are generally recommended as part of a zone tillage system as they are effective tools to reduce compaction and increase root proliferation in the surface horizon and subsoil.

Frost Tillage

Frost tillage does not refer to a specific implement but is a technique that can be performed in the winter when the surface 1 to 4 inches of soil is frozen and it has little snow accumulation. When frost enters initially unfrozen soil, water is rapidly moved upward toward the freezing front, thereby drying the soil underneath. This makes the soil tillable, as long as the frost layer is not too thick to prevent its fracturing by a tillage tool. Frost tillage is best performed with a shank-type tillage tool such as a chisel but can also be done with deep tillage tools and zone builders. Verification of a dry subsoil is important to ensure good shattering in the unfrozen layers of the soil and prevent smearing. Subfreezing air temperatures are important during the tillage operation to maintain a frozen soil surface and prevent tire slippage. A light snow cover is not a problem as long as it develops after the frost entered the ground and sufficient traction is available. Frost tillage allows for primary tillage on a field when the surface is frozen and can support the field equipment without compaction. It results in an extremely rough soil surface consisting of large randomly cast plates of frozen soil, which are very favorable for water infiltration and erosion prevention, even after soil melting. Frost-tilled fields generally require only light secondary tillage in the spring.

Frost tillage yields are consistently identical to those under conventional spring chisel tillage. The power requirements per shank (15–20 hp) are higher than those for unfrozen chisel tillage. Frost tillage is advantageous by shifting fall or spring workload to the winter. It is particularly attractive when wet weather in the fall prevented field work. It also allows for incorporation of winter-applied amendments including manure, thereby reducing the risk for runoff during snowmelts and rains in the late winter and spring. Direct injection of liquid manure under frost tillage conditions has been successfully performed but has not yet been fully researched. Frost tillage is generally possible for time windows ranging from one to eight days, depending on weather conditions. The average number of frost tillage days per winter is four for central and southern New York (Fig. 10). In northern New York, frost tillage conditions are generally less prevalent.

Selecting a Tillage System

The best tillage system for any field is difficult to define and depends on many factors. The general objectives in selecting a

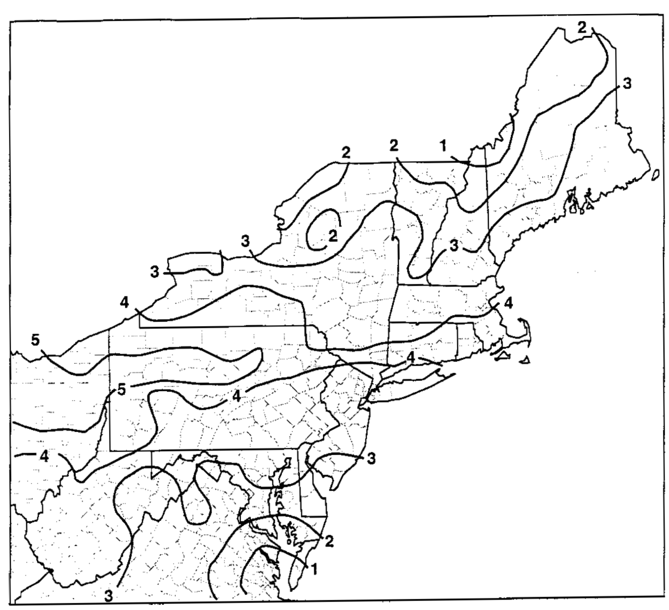

Fig. 10. Average number of frost tillage days in the Northeast

Table 2. General adaptability ratings for tillage systems for row crop production by soil management group based on yield potential and cost of production

Soil Management Group		*Moldboard Plow*		*Chisel Tillage*			*Ridge Tillage*	*Zone Tillage*	*No-Tillage*	*Deep Tillage*
		fall	*spring*	*fall*	*frost*	*spring*				
Group IA,B	clays and silty clay loams									
Group IIIB	heavy silts with fragipan	2	4	2–3	2–3	3	1–2	2–3	5	4
Group IIA,B	silt loams	3	3	2–3	2–3	2–3	1–2	2–3	4	3
Group IIC	silt loams	5	2	4	3–4	2	3	1–2	2	4
Group IIIA	coarse sands and gravels									
Group IV	sands and coarse loams									
Group V	sands and gravels	5	2	4	2–3	2	2	1	2	2

Notes:
- 1 = highly adapted, 5 = poorly adapted
- Ratings do not include environmental concerns. These should be evaluated separately based on site-specific information.
- Relative rankings apply only within a row. Deep tillage rankings apply only when subsoil compaction is present.
- Adaptability of reduced tillage systems may be lower when soils are severely compacted or poorly drained.
- No-, zone, and ridge tillage generally perform better in strict corn-soybean rotations.

tillage system should include the following (not necessarily in ranked order):

Maximum Economic Return

Table 2 lists adaptability rating of tillage systems for annual row crops for the different soil management groups based on potential economic return. Relative rankings apply only within each soil management group (rows in the table). In general, coarse-textured soils are better adapted to reduced tillage performed in the spring. Ridge tillage has been found to perform well on fine and medium-textured soils and is recommended for lands that are in long-term row-crop production. Restricted tillage systems also perform better in crop rotations. Notably, corn after soybean under under such systems outyields continuous corn.

Tillage systems have specific requirements for equipment, labor and crop inputs, and variable costs of production. Fuel requirements for no-till are less than 50 percent of those for moldboard plow systems and labor costs are 40 percent lower. Herbicide costs may be higher, however, especially in the early transitional years, and delayed maturity may increase grain drying costs in some years. The highest-yielding tillage system therefore does not necessarily provide the greatest economic return, and a few bushels per acre less under conservation tillage may be more than offset by lower production costs. *In all cases, it is highly advised to invest in zone-till or other sophisticated conservation tillage planters because they provide the greatest flexibility in soil management and allow for experimentation with reduced tillage.*

For organic farms, full-width tillage is typically a necessity because of the need for mechanical weed control and incorporation of organic fertilizer sources. Organic farming on lands that are prone to erosion may therefore involve an inherent tradeoff. Soil structure generally is more easily maintained as these farms use more organic inputs such as manures and composts, and heavily rely on crop rotations and cover crops to break pest cycles. Additional structural conservation practices and the use of modern planters to establish good crop stands without excessive secondary tillage can reduce erosion concerns.

Tillage guidelines for nonrow crops vary as some soil management systems, notable ridge and zone tillage, are not appropriate. Fine seedbeds are generally more desirable with cereal and perennial forage crops, depending on the type of seeding equipment. Similar to row crops, the use of no-tillage can be successful when compaction and drainage problems are minimal.

Maximum Surface Cover

Relative soil loss decreases rapidly with increasing surface residue levels (Fig. 5) and protects the soil from heat and temperature extremes. The amount of residue left on the soil surface after tillage is affected by the amount of residue produced (crop type, yield, harvesting method), overwintering, and the type and number of tillage passes. Table 3 may be applied to estimate residue levels from various field operations and weathering by multiplying the remaining percentages of residue for each tillage pass, starting with the initial residue levels. For example, assuming 80 percent residue cover after corn harvest for grain, a typical residue level after planting may be

80% (initial) x 90% (overwintering) x
70% (spring chisel with straight points) x
60% (finishing disk, light setting) x
85% (planter with fluted coulters) =
25.7% final residue cover

Residue cover may be field estimated by using the Natural Resources Conservation Service (NRCS) "line-transect method." It involves a measuring tape that is laid out over the soil surface in representative areas. Residue cover is assessed by counting the relative number of tape 1-foot marks that lie directly over a piece of residue. For more information on this method, contact your local NRCS office.

Minimum Tillage Intensity and Energy Use

Fuel costs and air pollution from diesel consumption for tillage should be minimized for economic and environmental reasons. Intensive tillage also increases organic matter oxidation, contributing to soil degradation and carbon dioxide emissions into the atmosphere. On lands with complex topography, intensive tillage increases soil translocation and loss of topsoil on the upper slopes. More than one secondary tillage pass often cannot be justified in row crops when using a conservation planter.

Optimal Timing

If tillage or planting is performed when the soil is too wet, i.e., its consistency is above the plastic limit (Fig. 7), then cloddyness and poor seed placement may result in poor stands. Therefore, it is always recommended to do the ball test (p. 16) on soil from the lower part of the plow layer to ensure that field conditions are right. Tillage is also not recommended when the soil is too dry as it may be hard, especially when compacted, and create excessive dust.

Table 3. Estimated percent residue cover remaining on the soil surface after specific implements and field operations (Adapted from *Estimates of Residue Cover Remaining after Single Operation of Selected Tillage Machines*, SCS, EMI, and University of Nebraska)

Implement	*Nonfragile residue remaining*
Plows:	
Moldboard plow	0–10
Disk plow	30–40
Machines that fracture soil:	
Paratill/paraplow	70–90
V ripper/subsoiler:	
12–14 in. deep, 20-in. spacing	60–80
Combination tools:	
Subsoil-chisel	50–70
Disk-subsoiler	30–50
Chisel plows with:	
Sweeps	70–85
Straight chisel spike points	60–80
Twisted points or shovels	40–70
Combination chisel plows:	
Coulter chisel plows with:	
Sweeps	60–80
Straight chisel spike points	50–70
Twisted points or shovels	30–60
Disk chisel plows with:	
Sweeps	60–70
Straight chisel spike points	40–60
Twisted points or shovels	20–50
Undercutters:	
Stubble-mulch sweep or blade plows with:	
Sweep/V-blade 30 in. wide	75–95
Sweeps 20–30 in. wide	70–90
Disk harrows:	
Offset	
Heavy plowing, 10-in. spacing	25–50
Primary cutting, 9-in. spacing	30–60
Finishing, 7- to 9-in. spacing	40–70
Tandem	
Heavy plowing, 10-in. spacing	25–50
Primary cutting, 9-in. spacing	30–60
Finishing, 7- to 9-in. spacing	40–70
Light tandem disk after harvest, before other tillage	70–80
One-way disk with:	
12- to 16-in. blades	40–50
18- to 30-in. blades	20–40
Single gang disk	50–70
Field cultivators *(including leveling attachments)*	
Used as the primary tillage operation:	
Sweeps 12–20 in.	60–80
Sweeps or shovels 6–12 in.	35–75
Duckfoot points	35–60
Field cultivators as secondary operation following chisel or disk:	
Sweeps 12–20 in.	80–90
Sweeps or shovels 6–12 in.	70–80
Duckfoot points	60–70
Finishing tools:	
Combination finishing tools with:	
Disks, shanks, and leveling attachments	50–70
Spring teeth and rolling basket	70–90
Harrows:	
Springtooth (soil tine)	60–80
Spike tooth	70–90
Flex-tine tooth	75–90
Roller harrow (cultipacker)	60–80
Packer roller	90–95
Rotary tiller:	
Secondary operation 3 in. deep	40–60
Primary operation 6 in. deep	15–35
Rodweeders:	
Plain rotary rod	80–90
Rotary rod with semi-chisels or shovels	70–80
Strip tillage machines:	
Rotary tiller, 12 in. tilled on 40-ft. rows	60–75
Row cultivators *(30 in. and wider):*	
Single sweep per row	75–90
Multiple sweeps per row	75–85
Finger wheel cultivator	65–75
Rolling disk cultivator	45–55
Ridge till cultivator	20–40
Unclassified machines:	
Anhydrous applicator	75–85
Anhydrous applicator with closing disks	60–75
Subsurface manure applicator	60–80
Rotary hoe	85–90
Bedders, listers, and hippers	15–30
Furrow diker	85–95
Mulch treader	70–85
Drills:	
Hoe opener drills	50–80
Semi-deep furrow drill or press drill (7- to 12-in. spacing)	70–90
Deep furrow drill with 12-in. spacing	60–80
Single disk opener drills	85–95
Double disk opener drills (conventional)	80–95
No-till drills and drills with the following attachments in standing stubble:	
Smooth no-till coulters	85–95
Ripple or bubble coulters	80–85
Fluted coulters	75–80
No-till drills and drills with the following attachments in flat residues:	
Smooth no-till coulters	65–85
Ripple or bubble coulters	60–75
Fluted coulters	55–70
Row planters:	
Conventional planters with:	
Runner openers	85–95
Staggered double disk openers	90–95
Double disk openers	85–95
No-till planters with:	
Smooth coulters	85–95
Ripple coulters	75–90
Fluted coulters	65–85
Strip till planters with:	
2 or 3 fluted coulters	60–80
Row cleaning devices	60–80
(8- to 14-in. wide bare strip using brushes, spikes, furrowing disks or sweeps)	
Ridge-till planter	40–60
Climatic effects:	
Over winter weathering	
Following summer harvest	70–90
Following fall harvest	80–95

Fall tillage is generally not recommended for row crops except (1) on high plasticity soils such as clays and clay loams that do not sufficiently dry in the spring, (2) when soils are severely compacted and would then benefit more from freeze-thaw action, (3) for deep tillage, or (4) when used to establish a fall-seeded (cover) crop. In all cases, fall tillage must be evaluated against erosion concerns, and both surface roughness and residue cover should be maximized. Frost tillage provides an alternative to fall tillage that allows for some of its benefits, but reduces the erosion concerns. It is also a fallback option when conditions were too wet for autumn tillage.

Water Quality Concerns

When soil amendments such as manure and compost are used, effective and timely incorporation is important to conserving their nutrient value and reducing the potential for environmental losses through runoff and atmospheric losses. In many cases, tradeoffs may exist between erosion control (favoring no tillage) and nutrient and pathogen losses (favoring incorporation). It is recommended to use incorporation methods that maximize surface residue levels and minimize tillage intensity. Direct injection of amendments is generally the optimal approach to meet both agronomic and environmental objectives.

Chemical leaching is increased with tillage systems that involve no or minimal soil disturbance. This normally does not result in groundwater contamination problems, but care should be taken with adopting no-till or zone-till systems in areas with highly sensitive shallow aquifers, especially when used for drinking water.

Ridge tillage typically involves a ridge-cultivation operation in late spring. This allows for a 60 to 70 percent reduction in the use of herbicides if they are band-applied on the plant row. Conservation tillage cultivators can also be effectively used to reduce chemical inputs with other tillage systems, including no-till and zone-till.

Other Considerations

Weather conditions, drainage and compaction problems, crop type, rotation sequence, labor availability, pest control, management skills, and equipment availability are additional important factors in choosing the most appropriate tillage and planting system.

Soil Testing

Why Test Soil?

Soil testing is the building block of a fertilizer management program. The results of the soil test program help growers produce maximum economic yields. Guidelines from Cornell's soil testing program for the amounts of lime and fertilizer necessary to produce optimal yield are made after considering nutrient availability in the soil, soil type, crop rotation, and manure management practices. Guidelines include other important information for nutrient management, such as the timing, method, and placement of fertilizers and lime to increase their effectiveness.

Soil testing serves agriculture and the public in another important way. A correctly managed soil fertility program minimizes nutrient losses while maximizing economic returns. A poorly managed program can contribute to water pollution because of overfertilization and improper timing or placement of fertilizer, and to poor yields because of underfertilization or inadequate soil pH.

What Is a Soil Testing Program?

A good soil testing program is based on a knowledge of (1) soils and their production potential, (2) crop rotation sequence, (3) cultural and manure management practices, and (4) chemical soil analysis determined in the laboratory.

A lime and fertilizer guideline is developed only after linking these four components together. A soil testing program is much more than simply estimating the residual nutrient values in the soil by a chemical analysis.

How Does a Soil Test Work?

Soil test analyses are rapid chemical tests that measure a portion of the total supply of nutrients in the soil. The soil tests must be calibrated with crop yields through laboratory and field research to determine the maximum economic response for lime and fertilizer. The soil testing laboratory combines the results of the soil analysis with the grower's crop and soil information and the research calibration results to provide a guideline based on the relationship between the soil test analysis and the outcome of fertilizer experiments.

It is often difficult to relate soil test results and guidelines from two or more laboratories. Most laboratories, unfortunately, do not use the same chemical procedures for the soil analyses. Therefore, the amount of nutrients extracted from the same soil sample will differ between laboratories. Soil test values are meaningful only if they have been calibrated with field experiments. One should be cautious about using the results and guidelines from laboratories that do not maintain a local field research program to calibrate their soil tests with economic crop response. Using nutrient replacement based on total crop removal, soil nutrient balances, or nutrient buildup usually overestimates the fertilizer needs for maximum economic yield.

How to Collect and Submit a Soil Sample

To collect and submit a soil sample properly for a complete analysis, one needs a soil test kit and information about the field being sampled, such as crop rotation, soil type, and cultural and manure management practices.

1. Purchase a soil test kit from your local Cornell Cooperative Extension agent or order one from the Cornell Nutrient Analysis Laboratories, 804 Bradfield Hall, Cornell University, Ithaca, NY 14853-1901. The soil test kit consists of a cloth mailing bag with a mailing envelope, plastic bag, information sheet, and instructions. The cost of the kit covers the standard soil tests for pH, lime requirement, phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg), aluminum (Al), iron (Fe), manganese (Mn), zinc (Zn), nitrate-nitrogen (NO_3-N), and organic matter. No-till pH is also included in the standard tests when relevant. There is an additional charge of $5 for boron (B) and $2 for soluble salts, which should be returned with the completed information sheet.

2. Use the right sampling tools. A soil probe or auger is best. If you use a garden spade or shovel, be sure to collect a constant volume of soil with depth. Use a clean plastic bucket to collect the soil. Metal buckets and some paper bags may contaminate the sample.