Soil Management

TABLES

FIGURES

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Sincere thanks to Phil Kolb and Doug Miller for preparing Figures 1.1-1, 1.1-2, 1.1-5, 1.1-6, and 1.1-7, and to Doug Miller, William Waltman, and Ed Ciolkosz for their help in developing the no-till management intensity classification.

THE SOILS OF PENNSYLVANIA

Twelve broad soil regions can be distinguished in Pennsylvania (Figure 1.1-1). They are described in the sections that follow.

1. Eastern Lake Shore

The soils on the shores of Lake Erie developed in beach sand and lacustrine silts and clays. The soils developed in the beach sands are mostly sandy and gravelly and have rapid internal drainage, although some have a shallow water table where the silts and clays underlie the beach deposits. The landscape is mostly level, and erosion potential is therefore low. The lacustrine soils generally contain few rock fragments and have moderate root zone available water-holding capacity. This region has a mild climate due to the proximity of Lake Erie, making it suitable for the cultivation of rather unique crops such as grapes.

2. Glaciated Region of the Appalachian Plateau

The soils in northwest Pennsylvania are derived from glacial till. Glacial till is a dense material that was once under huge masses of ice (glaciers). Water percolates very slowly through the till. Many soils in this region also have a fragipan, a dense subsoil that cannot be penetrated by roots and allows very slow water and air movement. The poor drainage of many soils in this region is characterized by gleying (gray color of reduced iron) and mottling (spots of color) caused by a perched seasonal high water table and impeded percolation.

The landscape is mostly level or undulating, and erosion potential is low to moderate. Rock fragments can be present if the till is near the soil surface. The root zone available water-holding capacity of these soils is primarily determined by the depth to the impermeable layer. If the soil is shallow, crop roots will have a small volume of soil to explore for water. The result is that crops may suffer drought stress in summer on soils that are saturated in spring. Although the growing season is short, the soils in this area can be highly productive if properly drained.

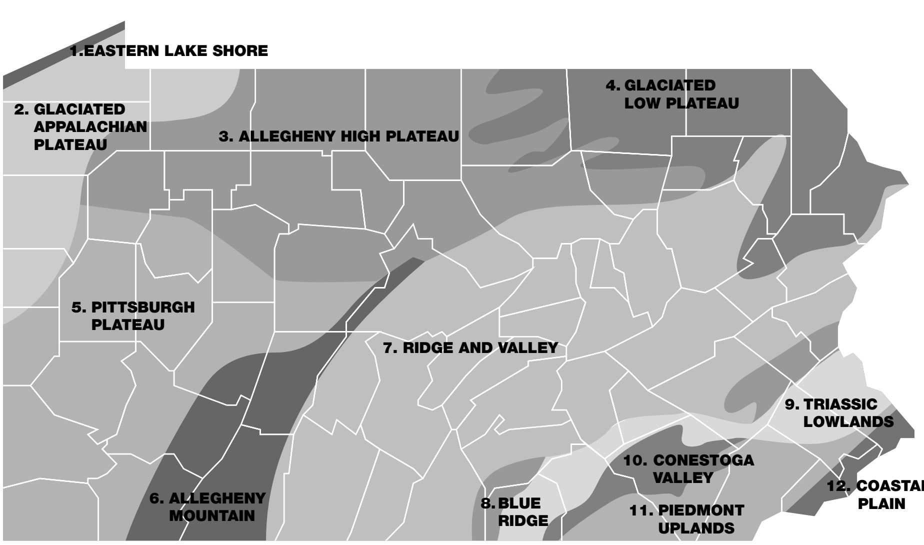
3. Allegheny High Plateau

Soils in the Allegheny High Plateau of northcentral Pennsylvania developed primarily in sandstone. The dominant texture of these soils is sandy loam. They are mostly well drained. If slopes are steep, erosion potential is substantial. Rock fragment content can be high. The root zone available water-holding capacity of these soils is often low due to their coarse texture and the presence of rock fragments. The growing season in this region is short (<100 days) because of the high elevation. Due to their low agricultural productivity, most soils of the Allegheny Plateau are under forest vegetation, but there are some notable exceptions, such as potato and pasture production.

4. Glaciated Low Plateau

The soils in northeast Pennsylvania are derived from glacial till. The till in this area is typically more discontinuous than in the northwestern portion of the state. Some of these soils have a fragipan at shallow depth and therefore are somewhat poorly to poorly drained. The surface texture of these soils is predominantly silt loam. The landscape is undulating and the erosion potential is low to moderate. Rock fragments are common in the soils of this area. Some of the soils have very low root zone available water-holding capacity due to their limited rooting depth. The growing season is short due to the elevation and northern latitude.

Figure 1.1-1. Soil regions of Pennsylvania.



5. Pittsburgh Plateau

The Pittsburgh Plateau in central and southwest Pennsylvania is dominated by soils developed in acid clay shales and interbedded shales and sandstones. These soils contain more clay and silt than those derived from sandstone. The surface texture of these soils is predominantly silt loam. The soils are usually well drained. The landscape of this region has rather steep slopes, and erosion is a major concern. Many of these soils also contain substantial amounts of rock fragments. The root zone available water-holding capacity of many soils in this region is moderate due to their limited depth. However, in the southwest region of this area, soils tend to be deeper and have a moderately high root zone available water-holding capacity. The growing season is rather short in most of the area, with the exception of the southwest. Agriculturally, the most productive area is located in the southwest of this region.

6. Allegheny Mountains

The Allegheny Mountain section is dominated by soils developed in sandstone. The texture is mostly sandy loam to loamy sand. Drainage is good. The landscape is often steeply sloping, and erosion potential is high. Rock fragments are common, resulting in low root zone available water-holding capacity. The high elevation of the Allegheny Mountain section gives this region a short growing season (<100 days). Much of this area is under forest vegetation, although there are some important agricultural areas.

7. Ridge and Valley Province

The ridges and valleys in the central/eastern part of Pennsylvania are a distinct landscape characterized by sandstone ridges, shale footslopes, and shale and limestone valleys. Sandy loam soils similar to those on the Allegheny High Plateau and Allegheny Mountains sections are found on the forested ridgetops. Colluvial soils that are a mixture of sandstone and shale are found on the slopes. In the valleys, limestone-derived soils predominate, although some are shale-derived. The limestone-derived soils are among the most productive in Pennsylvania. They are usually deep, well drained, have high root zone available water-holding capacity, and have few rock fragments. The shale-derived soils are less productive because of their acidic nature, steep slopes, and generally low root zone available water-holding capacity. The soils in the valleys are on level or undulating land, and erosion potential is low to moderate. The valley soils are used intensively for agriculture.

8. Blue Ridge

The Blue Ridge province covers eastern Franklin, southern Cumberland, and western Adams Counties. The soils in this area are derived primarily from igneous and metamorphic rocks. Igneous rocks are of volcanic origin. Metamorphic rocks have been altered under great pressure below the surface of the earth. The soils in these areas are generally well drained. Their surface texture is silt loam. They often contain significant amounts of rock fragments. Steep slopes are common, giving many soils in this area high erosion potential. The root zone available water-holding capacity of the soils is commonly moderate. The high elevation results in a short growing season. Much of this area is under forest.

9.Triassic Lowlands

The soils in the Triassic Lowland section of the Piedmont developed in reddish sandstone, shale, and siltstone. The soils are generally silt loams, well drained, and located on sloping land. The erosion potential of these soils is moderate to high. The Abbottstown-Doylestown-Reading association in Bucks and Montgomery Counties is an exception to this rule. The soils in that part of this region are poorly drained and are located on level land. The soils in the Triassic Lowland section can contain substantial amounts of rock fragments. The root zone available water-holding capacity of these soils is moderate. The region has a long growing season.

10. Conestoga Valley

Limestone-derived soils predominate in the Conestoga Valley section. These soils are comparable to those in the valleys of the Ridge and Valley province. They have a silt loam surface texture and a clayey subsurface horizon. They are well drained. The landscape is level to undulating, and erosion potential is low. Rock fragments are scarce, and the root zone available water-holding capacity is high. The growing season is long. These are productive soils that are used intensively for agriculture.

11. Piedmont Upland

Soils in the Piedmont Upland section are predominantly derived from metamorphic rock. These soils have a silt loam texture, and are well drained. The landscape has rather steep slopes, and erosion potential is moderately high. Rock fragments are scarce on these soils. Their water-holding capacity is moderate to high. The growing season is long. These soils can be very productive if they are deep, and they are used intensively for agriculture.

12. Coastal Plain

The soils of the Coastal Plains section developed in coastal sands. These soils usually have a sandy surface texture and are well drained. Because the topography is level, erosion potential is typically low. The soils contain few rock fragments but have moderate root zone available water content due to the coarse soil texture. This region has the longest and warmest growing season of Pennsylvania. Most of the area is occupied by the city of Philadelphia and its suburbs.

Table 1.1-1 lists major soils of Pennsylvania, along with some of their properties and expected yield potentials.

Table 1.1-1. Selected properties and typical capabilities of major Pennsylvania soils.

Note: Ratings provide relative information for comparing soils and should not be used quantitatively.

Soil series	*Depth class*[1]	*Drain class*[2]	*Leaching potential*	*Crop prod. group*	*Corn grain bu/A*	*Corn silage T/A*	*Alfalfa T/A*	*Clover T/A*	*Wheat bu/A*	*Oats bu/A*	*Barley bu/A*	*Sorghum/ sudan T/A*	*Soybeans bu/A*
Abbottstown	D[5]	SWPD	1[7]	4	100	17	4[8]	2.5	40[8]	60	40[8]	17	30
Albrights	D[5]	MWD	1[7]	3	125	21	4	3	50	60	50	21	30
Allegheny	D	WD	2	1	150	25	6	4	60	80	75	25	45
Allenwood	D	WD	2	1	150	25	6	4	60	80	75	25	45
Alton	D	WD[6]	3	3	125	21	4	3	50	60	50	21	30
Alvira	D[5]	SWPD	1[7]	4	100	17	4[8]	2.5	40[8]	60	40[8]	17	30
Andover	D[5]	PD	1[7]	4	100	17	4[8]	2.5	40[8]	60	40[8]	17	30
Armagh	D	PD	1[7]	4	100	17	4[8]	2.5	40[8]	60	40[8]	17	30
Atkins	D	PD	1[7]	4	100	17	4[8]	2.5	40[8]	60	40[8]	17	30
Barbour	D	WD	2[7]	1	150	25	6	4	60	80	75	25	45
Basher	D	MWD	2[7]	2	125	21	5	3.5	60	80	75	21	40
Bath	D[5]	WD	1[7]	2	125	21	5	3.5	60	80	75	21	40
Bedington	D	WD	2	1	150	25	6	4	60	80	75	25	45
Berks	MD	WD	2	3	125	21	4	3	50	60	50	21	30
Birdsall	D	PD	1[7]	5	100	17	3[8]	2	40[8]	60	40[8]	17	30
Birdsboro	D	MWD	2[7]	1	150	25	6	4	60	80	75	25	45
Blairton	MD	MWD	1[7]	4	100	17	4[8]	2.5	40[8]	60	40[8]	17	30
Bowmansville	D	SWPD	2[7]	4	100	17	4[8]	2.5	40[8]	60	40[8]	17	30
Braceville	D[5]	MWD	1[7]	3	125	21	4	3	50	60	50	21	30
Brecknock	D	WD	2	2	125	21	5	3.5	60	80	75	21	40
Brinkerton	D	PD	2	4	100	17	4[8]	2.5	40[8]	60	40[8]	17	30
Brooke	MD	WD	1	2	125	21	5	3.5	60	80	75	21	40
Buchanan	D[5]	MWD	1[7]	3	125	21	4	3	50	60	50	21	30
Bucks	D	WD	2	1	150	25	6	4	60	80	75	25	45

continued

Table 1.1-1. Selected properties and typical capabilities of major Pennsylvania soils (continued).

Note: Ratings provide relative information for comparing soils and should not be used quantitatively.

Soil series	*Depth class[1]*	*Drain class[2]*	*Leaching potential*	*Crop prod. group*	*Corn grain bu/A*	*Corn silage T/A*	*Alfalfa T/A*	*Clover T/A*	*Wheat bu/A*	*Oats bu/A*	*Barley bu/A*	*Sorghum/ sudan T/A*	*Soybeans bu/A*
Calvin	MD	WD	2	3	125	21	4	3	50	60	50	21	30
Cambridge	D[5]	MWD	1[7]	3	125	21	4	3	50	60	50	21	30
Canfield	D[5]	MWD	1[7]	3	125	21	4	3	50	60	50	21	30
Cavode	D	SWPD	1[7]	4	100	17	4[8]	2.5	40[8]	60	40[8]	17	30
Chenango	D	WD[6]	3	2	125	21	5	3.5	60	80	75	21	40
Chester	D	WD	2	1	150	25	6	4	60	80	75	25	45
Chippewa	D[5]	PD	1[7]	4	100	17	4[8]	2.5	40[8]	60	40[8]	17	30
Clarksburg	D[5]	MWD	1[7]	3	125	21	4	3	50	60	50	21	30
Clymer	D	WD	2	2	125	21	5	3.5	60	80	75	21	40
Comly	D	SWPD	1[7]	3	125	21	4[8]	3	50	60	50	21	30
Conestoga	D	WD	2	1	150	25	6	4	60	80	75	25	45
Conotton	D	WD	2	2	125	21	5	3.5	60	80	75	21	40
Cookport	D[5]	MWD	1[7]	3	125	21	4	3	50	60	50	21	30
Croton	D[5]	PD	1[7]	4	100	17	4[8]	2.5	40[8]	60	40[8]	17	30
Culleoka	MD	WD	2	3	125	21	4	3	50	60	50	21	30
DeKalb	MD	WD	2	3	125	21	4	3	50	60	50	21	30
Dormont	D	MWD	1[7]	3	125	21	4	3	50	60	50	21	30
Duffield	D	WD	2	1	150	25	6	4	60	80	75	25	45
Duncannon	D	WD	2	1	150	25	6	4	60	80	75	25	45
Edgemont	D	WD	2	2	125	21	5	3.5	60	80	75	21	40
Edom	D	WD	1	2	125	21	5	3.5	60	80	75	21	40
Elliber	D	WD[6]	3	2	125	21	5	3.5	60	80	75	21	40
Erie	D[4]	SWPD	1[7]	4	100	17	4[8]	2.5	40[8]	60	40[8]	17	30
Ernest	D[5]	MWD	1[7]	3	125	21	4	3	50	60	50	21	30
Fredon	D	SWPD	1[7]	4	100	17	4[8]	2.5	40[8]	60	40[8]	17	30
Frenchtown	D[5]	PD	1[7]	4	100	17	4[8]	2.5	40[8]	60	40[8]	17	30
Gilpin	MD	WD	2	3	125	21	4	3	50	60	50	21	30
Glenelg	D	WD	2	1	150	25	6	4	60	80	75	25	45
Glenville	D[5]	MWD	1[7]	3	125	21	4	3	50	60	50	21	30
Guernsey	D	MWD	1[7]	3	125	21	4	3	50	60	50	21	30
Hagerstown	D	WD	1	1	150	25	6	4	60	80	75	25	45
Hanover	D[5]	WD	1[7]	2	125	21	5	3.5	60	80	75	21	40
Hartleton	D	WD	2	3	125	21	4	3	50	60	50	21	30
Hazelton	D	WD	2	2	125	21	5	3.5	60	80	75	21	40
Highfield	D	WD	2	1	150	25	6	4	60	80	75	25	45
Holly	D	PD	2[7]	4	100	17	4[8]	2.5	40[8]	60	40[8]	17	30
Hublersburg	D	WD	2	1	150	25	6	4	60	80	75	25	45
Huntington	D	WD	2	1	150	25	6	4	60	80	75	25	45
Klinesville	S	WD	2	4	100	17	4[8]	2.5	40[8]	60	40[8]	17	30
Kreamer	D	MWD	1[7]	3	125	21	4	3	50	60	50	21	30
Lackawanna	D[5]	WD	1[7]	2	125	21	5	3.5	60	80	75	21	40
Laidig	D[5]	WD	1[7]	2	125	21	5	3.5	60	80	75	21	40
Langford	D[5]	WD	1[7]	3	125	21	4	3	50	60	50	21	30
Lansdale	D	WD	2	2	125	21	5	3.5	60	80	75	21	40
Leck Kill	D	WD	2	2	125	21	5	3.5	60	80	75	21	40
Lehigh	D	MWD	1[7]	4	100	17	4[8]	2.5	40[8]	60	40[8]	17	30
Letort	D	WD	2	1	150	25	6	4	60	80	75	25	45
Lewisberry	D	WD	2	2	125	21	5	3.5	60	80	75	21	40
Lordstown	MD	WD	2	3	125	21	4	3	50	60	50	21	30
Manor	D	WD	2	2	125	21	5	3.5	60	80	75	21	40
Mardin	D[5]	MWD	1[7]	3	125	21	4	3	50	60	50	21	30
Meckesville	D[5]	WD	1[7]	2	125	21	5	3.5	60	80	75	21	40
Melvin	D	PD	1[7]	4	100	17	4[8]	2.5	40[8]	60	40[8]	17	30
Mertz	D	WD	1	2	125	21	5	3.5	60	80	75	21	40
Monongahela	D[5]	MWD	1[7]	3	125	21	4	3	50	60	50	21	30
Morris	D[4]	SWPD	2	4	100	17	4[8]	2.5	40[8]	60	40[8]	17	30
Morrison	D	WD	2	2	125	21	5	3.5	60	80	75	21	40
Murrill	D	WD	2	1	150	25	6	4	60	80	75	25	45
Neshaminy	D	WD	2	1	150	25	6	4	60	80	75	25	45
Opequon	S	WD	2	4	100	17	4[8]	2.5	40	60	40	17	30
Oquaga	MD	WD	2	3	125	21	4	3	50	60	50	21	30
Penn	MD	WD	2	3	125	21	4	3	50	60	50	21	30
Philo	D	MWD	2 [7]	2	125	21	5	3.5	60	80	75	21	40
Platea	D[5]	SWPD	1[7]	4	100	17	4[8]	2.5	40[8]	60	40[8]	17	30

continued

Table 1.1-1. Selected properties and typical capabilities of major Pennsylvania soils (continued).

Note: Ratings provide relative information for comparing soils and should not be used quantitatively.

Soil series	*Depth class*[1]	*Drain class*[2]	*Leaching potential*	*Crop prod. group*	*Corn grain bu/A*	*Corn silage T/A*	*Alfalfa T/A*	*Clover T/A*	*Wheat bu/A*	*Oats bu/A*	*Barley bu/A*	*Sorghum/ sudan T/A*	*Soybeans bu/A*
Pope	D	WD	2	1	150	25	6	4	60	80	75	25	45
Rainsboro	D	MWD	1[7]	3	125	21	4	3	50	60	50	21	30
Ravenna	D[5]	SWPD	1[7]	4	100	17	4[8]	2.5	40[8]	60	40[8]	17	30
Rayne	D	WD	2	1	150	25	6	4	60	80	75	25	45
Readington	D[5]	MWD	1[7]	3	125	21	4	3	50	60	50	21	30
Reaville	D	SWPD	1[7]	4	100	17	4[8]	2.5	40[8]	60	40[8]	17	30
Red Hook	D	SWPD	1[7]	4	100	17	4[8]	2.5	40[8]	60	40[8]	17	30
Sheffield	D[5]	PD	1[7]	4	100	17	4[8]	2.5	40[8]	60	40[8]	17	30
Shelmadine	D[5]	PD	1[7]	4	100	17	4[8]	2.5	40[8]	60	40[8]	17	30
Swartswood	D[5]	MWD	1[7]	2	125	21	5	3.5	60	80	75	21	40
Tunkhannock	D	WD[6]	3	2	125	21	5	3.5	60	80	75	21	40
Tyler	D	SWPD	1[7]	4	100	17	4[8]	2.5	40[8]	60	40[8]	17	30
Upshur	D	WD	1	2	125	21	5	3.5	60	80	75	21	40
Venango	D[5]	SWPD	1[7]	4	100	17	4[8]	2.5	40[8]	60	40[8]	17	30
Volusia	D	SWPD	1[7]	4	100	17	4[8]	2.5	40[8]	60	40[8]	17	30
Washington	D	WD	2	1	150	25	6	4	60	80	75	25	45
Watson	D[5]	MWD	1[7]	3	125	21	4	3	50	60	50	21	30
Weikert	S	WD[6]	2	4	100	17	4[8]	2.5	40	60	40	17	30
Wellsboro	D[5]	MWD	1[7]	3	125	21	4	3	50	60	50	21	30
Westmoreland	D	WD	2	2	125	21	5	3.5	60	80	75	21	40
Wharton	D	MWD	1[7]	3	125	21	4	3	50	60	50	21	30
Wheeling	D	WD	2	1	150	25	6	4	60	80	75	25	45
Wurtsboro	D[5]	MWD	1[7]	3	125	21	4	3	50	60	50	21	30
Wyoming	D	WD[6]	3	3	125	21	4	3	50	60	50	21	30

[1] Depth classes: D = Deep (>40"), MD = Moderately Deep (20-40"), S = Shallow (<20")
[2] Drainage classes: WD = Well Drained, MWD = Moderately Well Drained, SWPD = Somewhat Poorly Drained, PD = Poorly Drained
[3] Leaching ratings: These are only a relative rating of leaching potential. The higher the number, the greater the relative leaching potential.
[4] A fragipan is present at 10 to 16 inches (0.25 to 0.40 m) below the surface of the soil.
[5] A fragipan is present at 16 to 40 inches (0.40 to 1 m) below the surface.
[6] These soils are well drained to excessively well drained.
[7] These soils have a seasonal high water table that is less than 6 feet from the surface. Leaching potential may be a consideration of water resource use and water table following pesticide application.
[8] Crop not well suited for this soil.

SOIL HEALTH

Soil health[1] is now receiving more attention because of increasing recognition that many agricultural soils are "sick." Soil health is the ability of a soil to perform a desired function. In general, six functions of soils are distinguished. Soil is a:

1. Medium for plant growth
2. Recycling system for nutrients and organic wastes
3. Filtering and buffering system for water
4. Habitat for soil organisms
5. Store of carbon
6. Engineering medium for roads and buildings.

In agriculture, we are concerned with all but the last of these functions. The health of an agricultural soil is a composite result of the chemical, physical, and biological properties of the soil. These properties are partly a given—as discussed in the general soil regions in the first section of this chapter—whereas most properties are also influenced by soil management.

Box 1.1-1. Key soil physical and biological properties.

- Soil texture
- Soil depth
- Soil organic matter content
- Cation exchange capacity
- Bulk density
- Porosity
- Plastic/liquid limit
- Aggregate stability
- Water content
- Water-holding capacity
- Hydraulic conductivity (permeability)
- Infiltration
- Soil respiration
- Earthworms

One symptom of poor health of agricultural soils is their inferior tilth compared with that of neighboring virgin soils. Organic matter contents of agricultural soils are generally less than half that of soils under natural vegetation. Some soils seem to be "dead," having few if any visible living organisms in them. Soil erosion creates gullies in fields and may be carrying the most fertile portion of the soil, the topsoil, to streams. Sometimes, a crust develops after a heavy thunderstorm, leading to water runoff and poor crop establishment. Soil compaction also takes its toll, creating a dense layer that is impermeable to air and water and inhibiting root growth.

In some extreme cases, poor soil health has led farmers to abandon land. In other cases, crop yields have decreased. It is also possible that increasing amounts of fertilizers, pesticides, and tillage are needed to maintain yields. Therefore, an urgent need exists to improve soil health through changes in soil management.

1. Some people (especially scientists) prefer the term "soil quality," which means exactly the same thing as "soil health," the term used here.

In this section, we will discuss some key physical and biological properties of soil health (see Box 1.1-1). The chemical aspects of soil management are dealt with in the chapter on soil fertility.

Soil texture affects almost all other soil health indicators. It is the size distribution of primary soil particles that are smaller than 2 mm (0.79 inches). Sand (2–0.05 mm diameter), silt (0.05–0.002 mm) and clay (smaller than 0.002 mm) contents are used to determine the textural class from the textural triangle (Figure 1.1-2). Most soils in Pennsylvania are "silt loams." This classification refers to the surface soil and does not take into account differences in clay content in the subsoil, impermeable layers near the surface, rock fragments, etc. Soil texture is changed by tillage and soil erosion. Soil-inverting tillage (moldboard or disk plowing) mixes subsoil with topsoil. This can lead to an increase in clay content in the surface of soils that have a clayey subsoil. Soil erosion by water selectively removes fine silt-sized particles. Erosion by tillage moves topsoil downslope and is a major reason for the formation of clay knobs. Local information about soils can be gleaned from the county soil survey, available from your local USDA-NRCS office.

Soil depth is the depth of soil to bedrock or to an impermeable layer. Soil depth determines how deep roots, water, and air can penetrate into a soil. This, in turn, influences how much water can infiltrate the soil, how much water can be held by the soil, and how large a volume of soil can be occupied by plant roots. Soil tillage and erosion can lead to the loss of soil depth. Soil depth can be increased when soil is deposited in depressions or lower parts of the field, or if high quantities of compost, manure, or sludge are applied to the landscape.

Soil organic matter consists of living, partially to fully decomposed organic materials. Soil organic matter is typically 1 to 5 percent of the total dry weight of topsoil, with lower amounts in the subsoil. Different types of organic matter play unique roles in soil. Highly decomposed organic matter (also called humified organic matter) typically makes up 95% of the total soil organic matter, and contributes to the cation exchange capacity, the water holding capacity, and stability of small aggregates. Other, less highly decomposed types of organic matter such as polysaccharides are produced by bacteria and determine the stability of larger aggregates. Living organic matter such as fungal hairs and plant roots are also important for the stability of large aggregates. Soil organic matter is an important indicator of soil health. Its content can be increased by growing high-residue-producing crops; growing crops that produce large amounts of fine roots (species such as corn, small grains, grasses); growing cover crops; and by adding compost and manure (especially bedded manure). If crop residue is removed, for example, as hay or silage, care should be taken to supply residue in other forms such as a cover crop, compost, or manure. These steps will help maintain organic matter contents. Soil tillage increases losses of organic matter. Besides increasing the amount of residue added to soil, it is important to provide soil with a "diverse diet" of different types of organic materials.

The *CEC (cation exchange capacity)* of a soil is determined by the clay and organic matter content of a soil. These particles carry a negative charge that enables a soil to hold on to positively charged molecules called "cations." Potassium, calcium, and magnesium are nutrient cations that dissolve in water and would wash out of the soil if they were not held by the CEC. The CEC of your soil is reported on soil test reports.

Bulk density is a measure of the mass of particles that are packed into a volume (e.g., a cubic foot) of soil. If bulk density goes up, porosity goes down. It is favorable to have a low bulk density so that water and air can move through the soil. The optimal bulk density depends on soil texture. Ideal and problem bulk densities of different soils are given in Table 1.1-2. Soil compaction causes the bulk density to increase, whereas

Figure 1.1-2. The textural triangle quickly helps to determine the textural classification of a soil from the percentages of sand, silt, and clay it contains.

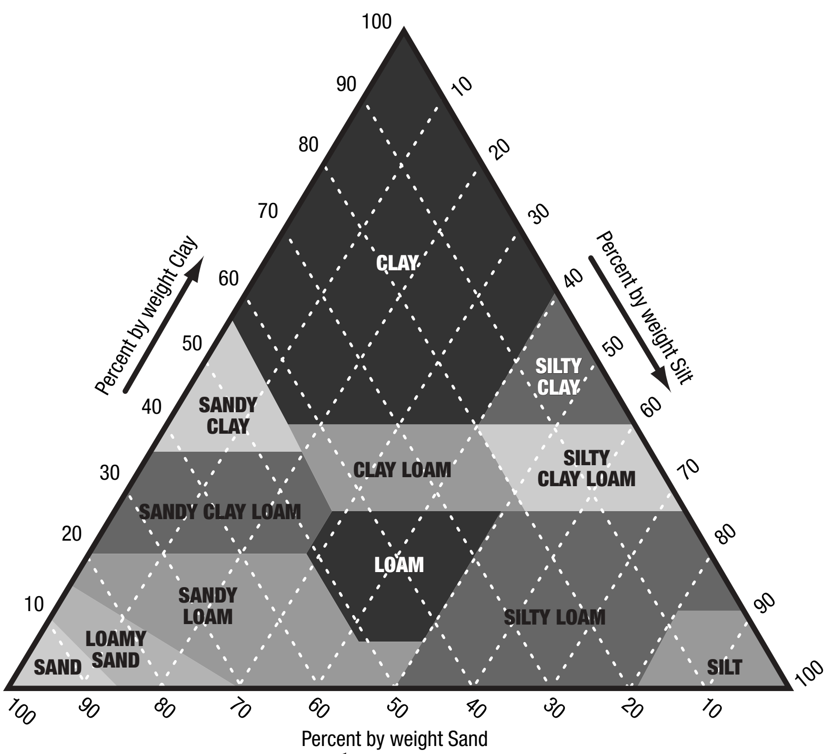


Table 1.1-2. Ideal soil bulk densities and root growth limiting bulk densities for soils of different textures.

Soil texture	*Ideal bulk densities*	*Bulk densities that may affect root growth*	*Bulk densities that may restrict root growth*
		g/cm^3	
Sand, loamy sand	<1.60	1.70	>1.80
Sandy loam, loam, sandy clay loam, clay loam, silt, silt loam, silty clay loam	<1.40	1.60	>1.75
Sandy clay, silty clay, clay	<1.10	1.50	>1.60

Source: generalized from USDA-NRCS soil quality test kit guide.

any practice that improves soil tilth decreases bulk density. Soil tillage temporarily decreases bulk density, after which the soil recompacts to similar (or greater) densities as a no-till soil at the end of the growing season. The moldboard plow and the offset disk compact the soil below the tillage tool.

Porosity is the total volume of pore space in a volume of soil. Some pores in a soil are filled with water, whereas others are filled with air (the "air-filled porosity"). A general rule of thumb is that roots need at least 10% air-filled porosity to be able to grow. The size distribution of the pores is also important because large pores act as conduits for water to move into the soil, whereas small pores hold water for plants to use when they need it. Large pores also allow oxygen to move into the soil and allow carbon dioxide to escape.

The plastic and liquid limit of a soil are two measures that are used to characterize the ease with which a soil can be compacted. The plastic limit is the moisture content at which it is possible to make a wire of approximately one-quarter inch in diameter by rolling the soil between two hands. The liquid limit is the moisture content at which soil starts to flow and act as a liquid. The difference between the plastic and liquid limit is the plasticity index. As a rule of thumb, the soil is most easily compacted when it is at the plastic limit, because it is at this moisture content that soil particles start to slide over each other and pack into greater densities. Traffic should therefore be avoided whenever the soil is at or wetter than the plastic limit. Soils with good tilth have a higher plastic limit than soils with poor tilth. This means that traffic is possible at higher moisture contents on soils with good tilth than on those with poor tilth.

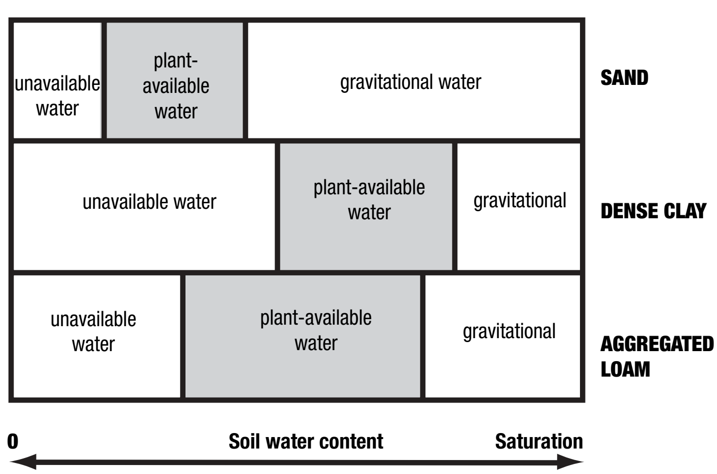
Aggregate stability is a measure of the stability of soil structure and soil tilth. Aggregates are conglomerates of clay, silt, and sand particles that are held together by physical and chemical forces. The bonds that hold these particles together can be broken by applying energy to the soil, for example, by shaking aggregates in water. A common method of determining aggregate stability is to place aggregates on a sieve with uniform openings and move the sieve up and down in a water bath. If a lot of soil passes through the sieve, the aggregate stability is low, while it is high if most soil remains on top of the sieve. Tillage destroys aggregates. Increasing soil organic matter content is the best method to increase aggregate stability. Crop rotations and crop mixtures can help to improve the aggregation of soils. Crops with extensive, fine root systems such as grasses and cereals stimulate aggregate stability in the long term. Crops with easily decomposed residue stimulate aggregate stability in the short term, because bacteria that feast on the residue produce polysaccharides that act as glue holding aggregates together. Amendments (such as manure or sewage sludge) that stimulate biological activity will help improve aggregate stability.

Water content is the mass of water divided by the dry mass of the soil. Water content changes all the time. *Water-holding capacity,* on the other hand, hardly changes during a year. Water-holding capacity is a measure of the amount of water available for plants to take up. The upper limit of water-holding capacity is called "field capacity." As a rule of thumb, the soil is at field capacity 24 hours after it has been soaked by rain. The lower limit of water-holding capacity is the "wilting point," at which crops completely wilt. Usually, crops start to suffer from drought long before they reach the wilting point. Water-holding capacity is determined by the texture, organic matter content, and structure (tilth) of the soil. Sandy soils have a low water-holding capacity because water content at both field capacity and wilting point is low (Figure 1.1-3). Much of the water in sandy soils is gravitational water that drains out quickly after a rainstorm. Clay soils usually have higher water-holding capacity than sandy soils. Clay soils contain low amounts of gravitational water, but they contain high amounts of water at wilting point. Well-aggregated loam soils, intermediate in texture between sand and clay soils, have the highest water-holding capacity. Any method that improves the tilth of soil, especially an increase in soil organic matter content, helps to increase the water-holding capacity.

Hydraulic conductivity (permeability) and *infiltration rate* are two closely related properties. Hydraulic conductivity is the rate of water movement in the soil, whereas infiltration is the rate at which water enters into the soil from the surface. Hydraulic conductivity and infiltration are determined by soil texture, changes in soil texture between surface and subsurface, impermeable layers, and depth to bedrock, as well as by soil management. Soil management that improves soil tilth also will help to increase water infiltration. Nightcrawler burrows, easily more than 3 feet deep, are very important for water infiltration. Soil tillage creates an immediate increase in infiltration, but as the growing season progresses, the infiltration rate decreases. In a no-tilled soil, infiltration rates are determined by macropores such as old root channels and earthworm burrows. On an annual basis, infiltration in long-term no-till soils often exceeds that in tilled soils because of the abundance of macropores, but it takes time to build up this pore system. Sealing and crusting also reduce water movement in bare soils with poor soil tilth.

Respiration measures the carbon dioxide produced by microbes that decompose organic materials. A high carbon dioxide flux (or respiration) indicates high levels of microbial activity. High respiration rates are indicators of a healthy soil if the soil is undisturbed. It is common to measure

Figure 1.1-3. Impact of soil texture and structure on plant-available water content.



extremely high respiration immediately after tillage. Soon after tillage, respiration rates will drop back to the same or a lower level compared with a soil that is not tilled. The rapid release of carbon dioxide immediately after tillage may be a result of the escape of carbon dioxide that was locked up in the soil, or the breaking up of aggregates that are brought into close contact with microorganisms, and is not considered an indicator of good soil health. A steady, high respiration rate throughout the year is desirable because it indicates that soil organisms are continuously restoring the soil. High soil porosity, optimum water contents, the application of a variety of organic materials by the use of crop rotations, cover crops, manure, and compost will feed microorganisms in the soil and increase respiration levels.

Earthworms generally increase microbial activity, increase the availability of nutrients, and enhance soil physical properties. They also accelerate the decomposition of crop residue by incorporating litter into the soil and activating mineralization and humification processes. Earthworms improve aggregation and porosity, suppress certain pests or disease organisms, and enhance beneficial microorganisms. There are different types of earthworms: some live in the surface of the soil and make horizontal burrows, while others live in the vertical burrows that can be more than 3 feet deep. Some earthworms make permanent burrows, while other earthworms fill their burrows with excretions.

Nightcrawlers are among the important earthworm species in agricultural soils. They make permanent, vertical burrows that provide channels for infiltration in no-till soils. They need surface residue, which they gather and deposit on top of their burrows. Tillage is detrimental to many, but not all, earthworm species. The species that make vertical burrows and need surface residue as a food source (such as nightcrawlers) are negatively affected by tillage. Earthworms do better in silt loams than in sandy or clayey soils. Earthworms flourish in well-drained soils, but not in poorly drained or droughty soils. The optimum pH range for earthworms is 5.0–7.4; they are scarce in soils with pH less than 4.5. This explains why some acidifying fertilizers, such as ammonium sulfate or urea, can have a negative impact on earthworms.

The quantity and quality of food available to earthworms often determines their density per acre. In many instances, crop residue contains too little nitrogen to be digested by earthworms. Manure applications, therefore, have been found to favor earthworm populations, because they help make the crop residue more palatable. Many fungicides and insecticides are toxic to earthworms. Most herbicides are not toxic to earthworms, with the exception of triazine herbicides, which are slightly toxic. A good method to monitor earthworm populations is to excavate one cubic foot (1 x 1 x 1 ft) of soil and count the earthworms in and beneath it. A good time to do this is after a rainstorm or early in the morning when the soil is moist, because earthworms tend to hide deeper when the soil is dry. Earthworms that reside below the foot-deep hole will come to the surface if you pour some mustard powder dissolved in water in the hole. Ten earthworms per square foot of soil surface is generally considered a good population in agricultural systems.

MONITOR YOUR SOIL HEALTH

The USDA-Natural Resources Conservation Service has developed a Soil Quality Test Kit for nonscientists that can be used to measure soil health in the field. The test kit contains tools to measure respiration, infiltration, bulk density, electrical conductivity, pH, soil nitrate, aggregate stability, slaking, and earthworm counts. More information about this test kit and how to purchase or build it can be obtained from the Department of Crop and Soil Sciences at Penn State. The test kit can be used to diagnose soil health problems and to compare effects of different soil management practices on soil health. Another useful tool for assessing soil health is the Pennsylvania Soil Quality Assessment Card, available through your county extension office. A summary of the observations accompanying the Score Card is given in Box 1.1-2.

Box 1.1-2. Indicators and rating of soil health.

	Descriptions		
Indicator	*Good (8-10)*	*Medium (4-7)*	*Poor (1-3)*
Soil tilth	Mellow, pliable, crumbly; clods fall apart easily	Firm, some large clods; clods can be broken apart by tillage	Hard dense chunks; tight, poor structure; difficult to break up clods by tillage
Compaction	Little resistance to penetration, no hard pan	Some resistance to penetration	High resistance to penetration, hard pan may be present
Infiltration and drainage	Soil drains well after rain, little ponding or runoff after rain	Water drains slowly with some ponding	Water ponds or runs off following most rains; soil surface crusted
Erosion	No gullies or rills; runoff is clear; deep topsoil	Some visual signs of erosion; cloudy runoff	Obvious signs of erosion; muddy runoff; shallow topsoil; subsoil at surface
Surface cover	Soil surface covered year-round; little bare soil	Some residue or vegetation present but soil not completely covered; bare soil during part of year	Little or no soil cover; bare soil for much of the year
Soil life	Signs of earthworms and other soil life common	Occasional signs of earthworms and other soil life	No visible signs of earthworms and other soil life
Soil organic matter	Dark color; visible organic material; earthy smell; high soil organic matter test	Medium soil organic matter test	Light color; no visible organic matter in soil; no smell; low organic matter soil test
Plant growth	Healthy, uniform plant growth; consistent good yields; crops resist stress, such as drought	Plant health varies; inconsistent yields; crops somewhat resistant to stress	Spotty, uneven crops; plants unhealthy; consistently poor yields; crops susceptible to stress
Plant roots	Robust, large, deep, well-dispersed root system; no obvious restriction to root growth; many fine roots	Roots present in profile; some misshapen roots; some restriction to root growth	Few or no roots present; roots are short, coarse, not uniformly distributed; roots growing sideways; obvious restrictions

Source: Pennsylvania Soil Quality Assessment fact sheet.

Soil tillage management for soil health

Status of Soil Tillage in Pennsylvania

Every two years, the USDA-NRCS, in collaboration with other agencies, performs a crop-residue survey that is published by the Conservation Tillage Information Center (CTIC) located in Lafayette, IN. The CTIC defines various tillage systems in its survey. See Box 1.1-3.

Conservation tillage is any tillage system that leaves more than 30% residue cover at planting, or more than 1,000 lbs/A of small-grain residue throughout the critical erosion period. Conservation tillage is the sum of no-tillage, ridge tillage, and mulch tillage. In Pennsylvania, the percentage of conventional tillage has remained constant the past 10 years at approximately 50% of planted acres (Figure 1.1-4). The area of reduced tillage has also remained constant at approximately 17% of planted acres. The total percentage of nonconservation tillage is therefore 67%. The area of mulch tillage decreased from 19% in 1990 to 13% in 2000. The largest portion of this decrease occurred between 1998 and 2000 and may be a temporary dip. The area of no-till increased slightly from 18% to 21% between 1990 and 2000. The crop residue survey therefore indicates that there has been little change in tillage management over the past 10 years.

The percentage of the planted acreage per county that was under nonconservation tillage (conventional and reduced tillage) is presented in Figure 1.1-5. In Figure 1.1-6, the percentage of no-till in each county is presented. The counties with the largest percentage of no-till are Adams, Blair, Clarion, Dauphin, Franklin, and Northumberland. The total planted acreage is very small, however, in Blair and Clarion Counties. In terms of acreage, the top no-till counties are York, Franklin, Northumberland, Chester, and Adams. The higher adoption of no-till in some counties is partially due to climatic and soil-related factors, as well as the type of farming system. Unfamiliarity or previous negative experiences with this technology may also explain differences in no-till adoption. In the next section, we will discuss the pros and cons of tillage and no-tillage, and will present a tillage recommendation zone classification for Pennsylvania.

Box 1.1- 3. Definition of tillage systems used by the Conservation Tillage Information Center.

Conventional tillage	Tillage systems that leave less than 15% residue cover at planting, or less than 500 lbs/A small grain residue equivalent throughout critical erosion period.
Reduced-till	Tillage systems that leave 15-30% residue cover at planting or 500-1000 lbs/A small grain residue equivalent throughout critical erosion period.
Mulch till	Full-width tillage system that disturbs the whole soil surface prior to and/or during planting. Leaves more than 30% residue cover at planting or more than 1,000 lbs/A of small grain residue throughout critical erosion period.
Ridge till	The soil is left undisturbed from harvest to planting except for strips up to 1/3 of the row width. Planting is completed on the ridge and usually involves the removal of the top of the ridge. Residue is left on the surface between the ridges. Ridges are rebuilt during cultivation. Ridge till is sometimes referred to as plant-till.
No-till and Strip-till	The soil is left undisturbed from harvest to planting except for strips up to 1/3 of the row width. Cultivation may be used for emergency weed control. No-till is sometimes referred to as direct seeding, slot planting, zero-till, row-till, and slot-till.

Source: National Crop Residue Management Survey, Conservation Tillage Information Center.

Figure 1.1-4. Development of tillage systems in Pennsylvania, 1990–2000.

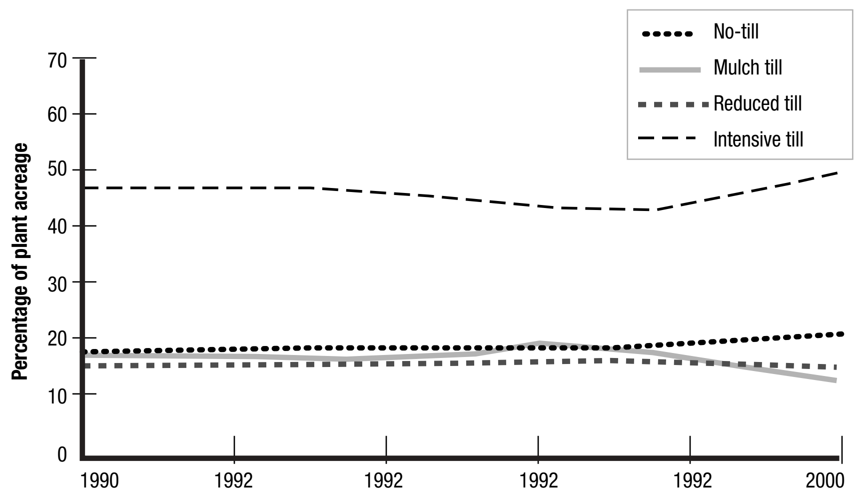


Figure 1.1-5. Nonconservation tillage in Pennsylvania in 2000.

Tillage versus no-tillage

Soil tillage is a very old practice that is deeply ingrained in the customs and traditions of Pennsylvania agriculture. New technology, however, allows the elimination of tillage without detrimental consequences for crop yields. In the following section, we highlight the reasons why farmers use soil tillage, discuss the validity of these reasons in today's agricultural systems, and touch on some of the disadvantages of tillage (See Box 1.1-4).

Reasons for tillage

Weed control

Weed control has been an important objective of tillage. However, with the judicious use of herbicides in an integrated weed control program, it is now possible to obtain excellent weed control without tillage (explained in Part 2, Section 1). The only exception where tillage for weed control is needed is in organic farming systems. However, although organic farmers cannot use herbicides, they can make use of integrated weed-control principles to limit tillage intensity. Keeping soil covered, reducing soil disturbance, and rotating crops are excellent ways to decrease the frequency of weeding.

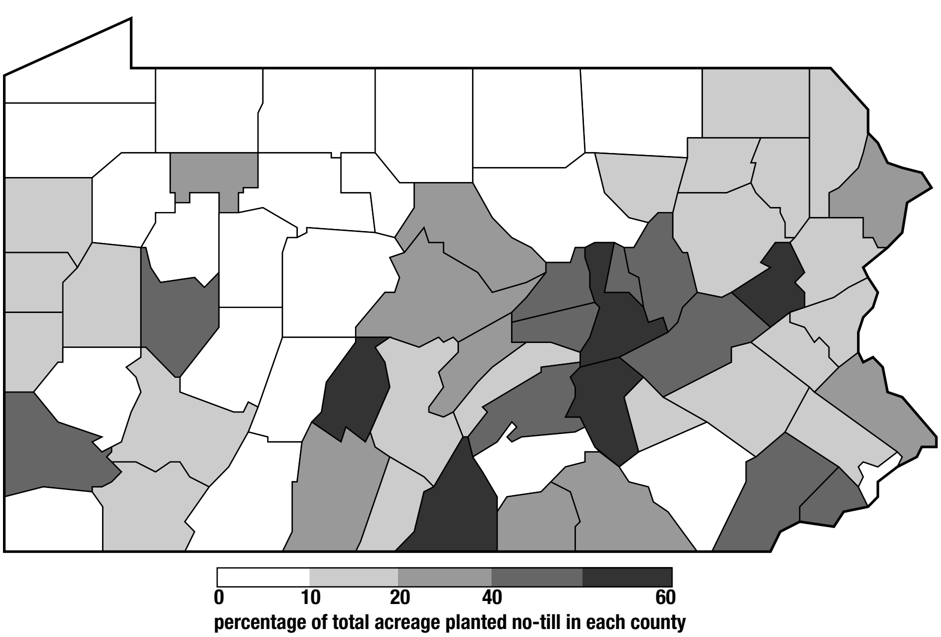
Seed bed preparation

Seed bed preparation is another traditional reason for using tillage that is becoming unnecessary. Modern planters and drills that enable the establishment of an optimum stand without tillage have been developed and are being refined. The most important differences between no-till planters and drills and conventional planters and drills are their residue-handling capacity, their ability to penetrate soils with high penetration resistance, and their closing wheels for firm soil. With proper attention to details, like adjusting downpressure and providing enough weight on the planter, it is possible to obtain excellent stands without tillage.

Box 1.1-4. Reasons for and disadvantages of soil tillage.

Reasons for tillage	*Disadvantages of tillage*
• Weed control	• Soil tilth destruction
• Seed bed preparation	• Stimulate soil crusting
• Root growth stimulation	• Increased evaporation
• Soil moisture control	• Decreased earthworm populations
• Soil temperature control	• More soil erosion
• Residue and manure incorporation	• More carbon losses
• Alleviation of compaction and ruts	• Bring rock fragments to surface
	• Labor requirements in busy period
	• Purchase and maintenance costs of equipment

Figure 1.1-6. No-till in Pennsylvania in 2000.



Root growth stimulation

Tillage is often promoted to stimulate root growth. In nature, however, roots grow without tillage. Problems with root growth in agricultural soils often occur when a soil lacks a permanent pore system and has poor tilth. Soil tillage destroys the natural pores created by decomposing roots, earthworms, and other soil-dwelling creatures. In addition, organic matter that improves soil tilth is mixed with soil and buried below the seed zone. Because of poor tilth, it is then necessary to loosen the soil to enable seed germination. This cycle makes the soil "addicted to tillage," and is probably a major reason why a temporary yield depression is sometimes observed in the first years after switching from a conventional tillage system to a no-till system. A good solution to this problem is to start no-tilling after the soil has been in a sod for a few years (assuming the soil has not been badly compacted by harvest equipment or manure spreaders). Once the soil ecosystem is restored, roots can grow in natural pores. It is observed that most roots of no-till crops are concentrated in the top 1 or 2 inches of the soil. Roots of crops grown in tilled soils, on the other hand, occupy the whole plow layer. Research has shown that the different distribution of roots is not negative for crop growth and yield. Roots tend to grow where the moisture and nutrients are, and this happens to be at the surface in a no-till system! Nevertheless, a few roots in deeper layers can save the day in a dry period.

Soil moisture control

Soil under tillage dries more rapidly than untilled soil that has residue cover. This may be a positive condition in a wet spring and on poorly drained soils, but may be detrimental on droughty soils where moisture deficits are common. Leaving crop residue at the soil surface reduces evaporation, particularly until canopy closure (Figure 1.1-7). Evaporation reduction with high-residue no-till is most important in southeast and southwest Pennsylvania where moisture deficits during summer are greater than in the northern sections of the commonwealth. Evaporation reduction is directly related to surface residue cover, and not to the absence of tillage, as such. A no-till system without surface residue cover will therefore not have improved soil moisture conservation compared to conventional tillage, while a chisel operation that leaves substantial amounts of crop residue at the surface will conserve moisture.

Another effect of reduced tillage is improved infiltration, especially in a no-till system with high residue cover (Figure 1.1-8). This is due to (1) the residue breaking the impact of raindrops that can cause seal and crust formation, (2) the physical obstruction of runoff water by residue, giving water a greater chance to infiltrate, and (3) more abundant and permanent earthworm and root channels that provide macro-pores through which water can infiltrate quickly. Any tillage practice that leaves substantial amounts of residue at the surface and disturbs the soil minimally can be expected to result in infiltration rates intermediate to those of a permanent no-till soil and an intensively tilled soil without crop residue cover.

Figure 1.1-7. Monthly evaporation in conventional tillage is greater than in no-till (data from Kentucky corn crop).

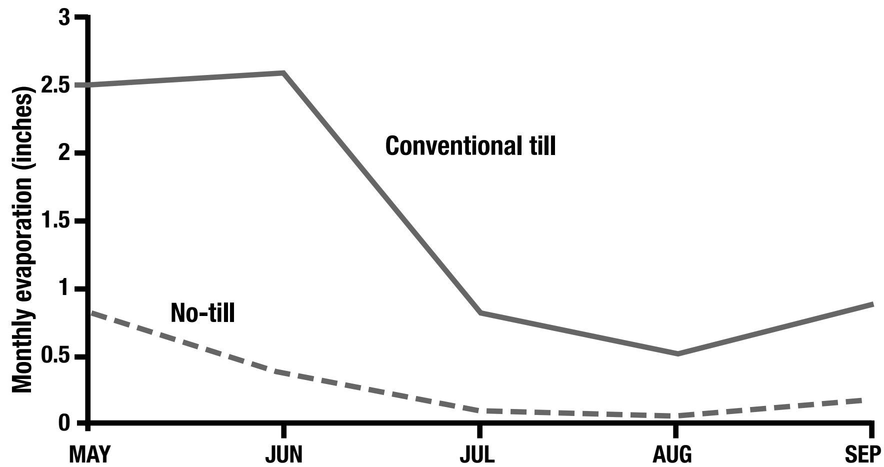
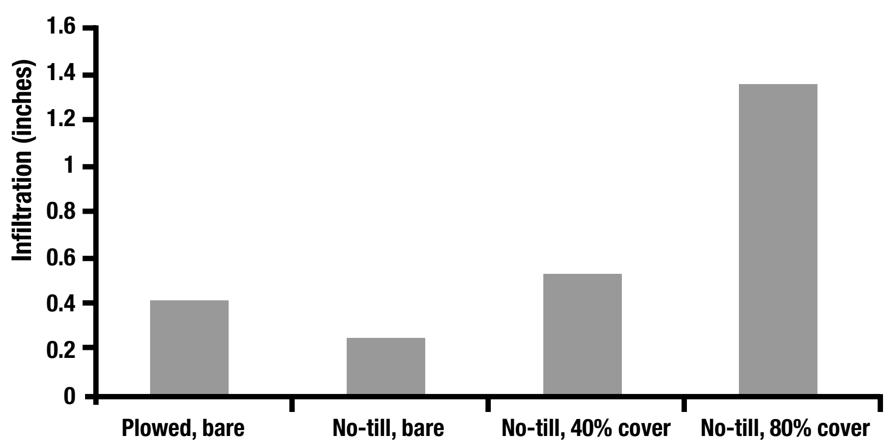


Figure 1.1-8. Typical effects of tillage and crop residue on infiltration (rainfall simulation experiment).



Soil temperature control

The average daily soil temperature below a mulched surface is lower than that beneath a bare surface. Soil temperature under crop residue is lower in the daytime, and higher at night, compared to soil temperatures under a bare surface. This is due to the interception of incoming radiation and the insulation of the soil by crop residue. At night, the residue-covered soil gives off less heat than the bare soil. The air above a no-till soil is therefore colder at night, increasing the chance of frost damage. Sub-optimum soil temperatures cause slower seedling growth, a common phenomenon in soils covered with much residue. Corn is especially sensitive to low soil temperatures, because its growing point stays below the surface for 30–45 days after planting. Research on well-drained soils has shown that low spring soil temperatures under no-till corn can significantly impact early growth and result in yield depression in areas with less than 2,800 GDD. If the growing season has more than 2,800 GDD, yields of no-till corn are not negatively affected by cold soil temperatures. In a long-term trial in Centre county (2,600 GDD), no-till yields have been equal to those of other tillage systems. Therefore, yield depression due to low soil temperatures under no-till continuous corn, probably will not materialize below Interstate 80, except where elevation is high.

In the northern tier of Pennsylvania, and at high elevations south of Interstate 80, yields of continuous corn can be expected to be depressed in no-till compared to tilled fields. In those areas of Pennsylvania with less than 2,800 GDD, special measures may be needed to move residue out of the row area, or to reduce the amount of residue left on the soil surface to allow more rapid warming of the soil in no-till. Row cleaners and fluted coulters in front of the openers can help move some residue and work up a limited amount of soil near the seed. Crop rotation of a high-residue-producing crop such as corn with a low-residue-producing crop such as soybeans, is an option to reduce the amount of surface crop residue at planting. It is also possible to harvest corn for silage, or bale some of the crop residue to reduce the thickness of residue cover. An appropriate balance has to be found between maximizing crop residue cover to improve soil health, and warming-up of the soil to obtain good germination and crop growth.

Incorporation of crop residue and manure

Every tillage operation causes incorporation of crop residue. A distinction is made between non-fragile and fragile residue based on size and amount of leaves and stems, total amount and density of plant material produced, and ease of residue decomposition. The distinction between non-fragile and fragile residue helps to calculate the amount of residue left at planting after weathering of residue and tillage operations. Typical amounts of residue cover left at harvest by some common crops grown in Pennsylvania are listed in Table 1.1-3.

Approximate amounts of residue left after some selected field operations are

Table 1.1-3. Typical percentages of crop residue cover left after harvest for different crops.

Crop	% cover after harvest
Non-fragile	
Alfalfa, legume or other forage	
Immediately after cutting	35
After regrowth	85
Barley[1]	75
Buckwheat	60
Corn	
Harvested for grain (60-120 bu/A)	80
Harvested for grain (120-200 bu/A)	95
Silage	15
Grain sorghum	
Harvested for grain	75
Silage	15
Oats[1]	80
Rye[1]	75
Spelt[1]	75
Tobacco	20
Triticale[1]	70
Wheat[1]	50
Fragile	
Canola/rapeseed	65
Dry edible beans	20
Soybean	70
Vegetables	20

[1] If straw is cut into small pieces, consider the residue to be fragile.
Source: MidWest Plan Service, 2000. Conservation Tillage Systems and Management, 2nd Edition.

Table 1.1-4. Estimated percent surface residue cover remaining after selected tillage operations, overwintering, and grazing.

	Non-fragile	Fragile
Tillage operations		
Moldboard plow	0-10	0-5
Disk plow	10-20	5-15
Paratill/paraplow	70-90	60-85
V-ripper or subsoiler (20” spacing, 13” deep)	60-80	40-60
Chisel with straight points	35-75	30-60
Chisel with twisted points	25-65	10-30
Tandem or offset heavy disk harrow	25-50	10-25
Field cultivator for primary tillage (sweeps 6-12” wide)	35-75	50-70
Field cultivator used for secondary tillage (sweeps 6-12” wide)	70-80	50-60
Finishing tools with spring teeth and rolling basket	70-90	50-70
Spring tooth harrow	60-80	50-70
Manure injector with chisel or sweep injectors	25-65	5-15
Climatic effects of over-wintering weathering (depend greatly on winter weather conditions)		
Summer harvested crops	70-90	65-90
Fall harvested crops	80-100	75-100
Fall operations (additional weathering)	85-95	80-95

Grazing by cows: Estimate reduction of residue cover for either fragile or non-fragile residue at 15% per 1000 lbs cow per acre per month, or 0.5% per cow per acre per day. Use the following formula to estimate residue remaining factor: 100 - (0.5 x (number of animals) x (average animal weight in lbs) x (number of days grazed) /(number of acres grazed)/1000]

Source: MidWest Plan Service, 2000. Conservation Tillage Systems and Management, 2nd Edition.

given in Table 1.1-4. To calculate the final expected amount of crop residue remaining after a tillage operation, multiply the percentages of residue remaining after each tillage operation. Table 1.1-4 is a guide to using tillage tools for a desired amount of residue, as detailed in Box 1.1-5.

An issue that is becoming very important for many farmers in Pennsylvania is how to reduce odor nuisance from manure applications. Neighbors in residential areas often complain about odors due to surface manure application. Tillage to incorporate manure is the first solution that comes to mind. Other practical solutions to reduce odor problems are to spread manure shortly before a rainstorm, band manure applications, and inject manure. Many problems can be avoided if farmers maintain good relations with neighbors through communication and education about farm practices.

Soil compaction alleviation

Alleviation of soil compaction is another reason to till soil. Many farmers forget, however, that tillage equipment also causes compaction. Below the moldboard plow and offset disk, it is common to find a compacted layer called a plowpan. This layer can restrict root growth and water and air movement in the soil. Each tillage pass involves driving over the soil, potentially compacting it. The following strategies are suggested to avoid compaction: (1) Drive on dry or frozen soil. Soil is most susceptible to compaction in a plastic condition (see soil health section for determining plastic condition). (2) Reduce the weight of farm equipment. The heaviest pieces of farm equipment are manure spreaders, forage wagons, self-propelled choppers, the combine, and the grain cart. Any vehicle with axle loads above 15 tons is likely to cause subsurface compaction, especially if the soil is wet. Heavy traffic should be restricted to field roads to avoid compacting the whole field. (3) Reduce the number of trips over the field. Most compaction occurs during the first trip, so every effort to reduce the amount of soil upon which vehicles are driven helps to reduce the impact of compaction. (4) Disperse the vehicle weight by increasing the contact area of farm vehicles with the

Box 1.1-5. Sample calculation of percent residue left after various field operations.

1. After harvest cover of high-yielding corn (non-fragile residue)	95%
2. Winter weathering	90%
3. Early spring chisel plowing, twisted shanks	40%
4. Field cultivator, secondary tillage	75%
5. Spring-tooth harrow and rolling basket	85%

95% (initial) x 0.90 (winter weathering) x 0.4 (chisel plowing) x 0.75 (field cultivation) x 0.85 (spring-toot harrow and rolling basket) = 22% at planting

Assuming this level of residue is less than desired, it may be possible to use a chisel plow with straight points while eliminating the field cultivator operation. This would result in:

1. After harvest cover of high-yielding corn (non-fragile residue)	95%
2. Winter weathering	90%
3. Early spring chisel plowing, straight points	50 %
4. Spring-tooth harrow and rolling basket	85%

95% (initial) x 0.90 (winter weathering) x 0.5 (chisel plowing) x 0.85 (spring-toot harrow and rolling basket) = 36% residue cover at planting ground. This can be achieved by using tracks, multiple axles, or double tractor tires. (5) Decrease tire pressure. Decreasing tire pressure increases contact area and reduces compaction. As a rule of thumb, the average contact pressure of a tire with the ground should equal the tire pressure. (6) Increase the resistance of the soil to compaction. This can be achieved through the judicious use of cover crops, crop rotations, and methods to increase organic matter content. Tillage methods to relieve soil compaction should disturb as little crop residue as possible.

Undesirable consequences of soil tillage

Destruction of soil tilth

Soil tilth is closely associated with the state of aggregation in soils. When a soil is tilled, roots and fungal hairs are broken and macro-aggregates break up. Micro-aggregates are not really affected by tillage in the short term. In the long term, however, once total organic matter contents decrease significantly, micro-aggregation also decreases because of natural degradation and a lack of new formation of micro-aggregates. Tillage also mixes crop residue and green manure with the soil, allowing microbes to “feast” on this material. The microbes release the short-lived compounds that glue particles together into aggregates. Once the plant remains have been decomposed, the supply of this glue stops and the macro-aggregates fall apart, especially at the surface of the soil where they are exposed to the impact of raindrops. This is the reason for the formation of crusts at the surface of tilled soils.

In a soil that is not tilled, roots and fungal hairs stay intact and maintain the stability of soil structure. It is possible, however, to maintain good tilth in a tilled soil by careful crop rotation (especially with perennial crops), use of cover crops that add root biomass and residue, and addition of manure and other sources of organic matter. Tillage leads to increased decomposition of organic matter; thus it is necessary to add more plant residue in such a soil to maintain or increase organic matter content for good soil structure.

Decrease in earthworm numbers

The number of earthworms decreases dramatically with intensive tillage (Table 1.1-5). A general rule of thumb is that earthworm numbers are reduced by 50% as a result of moldboard plowing. Some reasons for this decrease include: (1) the earthworms are killed by tillage, (2) the earthworms are eaten by birds when they are brought to the surface, (3) many earthworms need crop residue at the surface of the soil and starve after the residue is buried.

Table 1.1-5. Effect of crop and management on earthworm numbers (Indiana)

Crop	*Management*	*Earthworms/A*
Continuous corn	Plow	40,000
	No-till	75,000
Continuous soybean	Plow	230,000
	No-till	500,000
Clover/Ryegrass	Pasture	2,000,000
	Pasture + dairy manure	5,000,000

Source: MidWest Plan Service, 2000. Conservation Tillage Systems and Management, 2nd Edition.

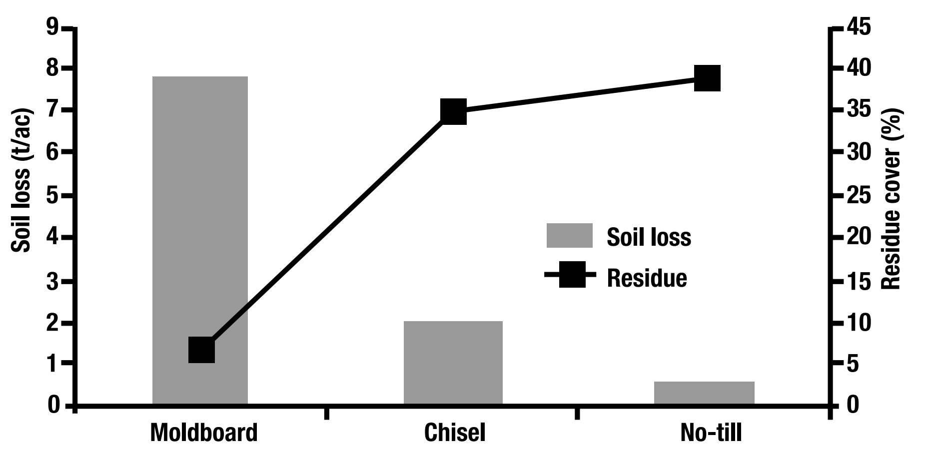
Soil erosion

Soil erosion from agricultural lands is still a concern in the United States, despite many decades of education and government programs to stimulate soil conservation. There are three forms of water erosion: sheet erosion, rill erosion, and gully erosion. Sheet erosion is difficult to see, because it is the movement of soil due to overland runoff. Rill erosion is the erosion in small rills in the field. Gully erosion leads to the formation of large channels and incisions in fields, and includes streambank erosion. Soil erosion has on- and off-farm effects. On the farm, soil erosion signifies a loss of the most fertile part of the soil which contains most of the organic matter. Eroded soil carries away fertilizers and pesticides. Gullies can interfere with farm operations. Erosion is most damaging on shallow soils or soils with high contents of rock fragments. Off-farm, eroded soil can clog drainage channels and pollute surface waters. The most effective way to reduce all three forms of erosion is by stopping soil and water movement at the source. This can be done if soil is protected from the impact of raindrops, and if infiltration is maximized. Although there are many ways to reduce erosion, we will focus on the effects of tillage in this section.

Soil tillage affects erosion in many ways. First, tillage buries crop residue. In the absence of cover, soil erosion begins with raindrop impact. Second, tillage destroys aggregates, facilitating the movement of loose particles that are easily eroded by water. Third, tillage destroys large, continuous pores such as earthworm burrows that are important for rapid water infiltration. Although no-tillage makes soil conservation easier, it does not guarantee erosion control. An example of soil erosion reduction with minimum and no-tillage is shown in Figure 1.1-9. This research shows that erosion control depends primarily on residue cover. If soil is bare, no-till will not offer soil erosion control.

The primary key to soil erosion control, therefore, is to maintain soil cover. If crop residue cover is low after harvest, for example after soybeans or corn silage, it is desirable to grow a cover crop to provide higher residue cover at planting. If soil is tilled, it is important to leave the soil bare for a minimum amount of time. This can be achieved by relay-planting a slowly establishing crop such as alfalfa in a fast-growing crop such as wheat. The nurse crop can be killed or harvested for silage when the main crop is well established. Another good soil erosion control practice is to plant crops on the contour in strips, alternating high-cover crops with low-cover crops and using buffer strips along

Figure 1.1-9. Example of erosion and residue cover moldboard, chisel, and no-till. (Rainfall simulation study, Nebraska, corn residue, 10% slope, silt loam.)



streams. USDA-NRCS personnel will help in the design of a soil conservation plan with your tillage system that can include contour strips, buffer strips, and stream bank protection.

Soil tillage has another effect that was not widely recognized until recently. Every time a soil is tilled, it moves downslope by gravity. This type of soil movement has been called "tillage erosion." Although tillage erosion only moves soil inside the field, it is probably the major reason for the appearance of clay knobs and rock outcrops on hillcrests.

Carbon losses

Carbon dioxide emissions to the atmosphere due to fossil fuel combustion and burning of natural vegetation are leading to an increase in the CO_2 concentration in the atmosphere. Growing evidence indicates this is causing a rise in the temperature of the world (the "greenhouse effect"). This temperature rise is expected to have many negative consequences, such as a rise in sea level, increased volatility of climate, and droughts in certain parts of the world. Many people are concerned about the greenhouse effect and believe steps need to be taken to decrease carbon dioxide concentrations in the atmosphere. Governments are discussing international treaties that would make countries responsible for reducing their carbon dioxide emissions to the atmosphere.

Soils contain carbon in their organic and inorganic matter (carbonates). While little can be done to increase the carbonate content of soils, it is possible to increase the organic matter content of soils. Such an increase would lead to storage of carbon in soils. Some U.S. policy makers are proposing plans to compensate farmers for increasing soil organic matter content. Some companies are already buying "carbon credits" from farmers or forest owners to compensate for the carbon dioxide they emit to the atmosphere. Although there is no certainty yet as to how this policy will evolve, farmers can prepare for the future by considering how their management affects the soil organic matter content.

There are two means to increase the organic matter content of soils: one is to increase the organic matter gains, the other is to decrease organic matter losses (Box 1.1-6). Soil tillage has been observed to increase the decomposition of organic matter compared to no tillage. Much of this decomposition takes place immediately after the soil is plowed and is directly related to the volume of soil disturbed and the roughness of the surface after plowing. The moldboard plow causes the largest amount of carbon losses, while a deep tillage tool that does not invert the soil causes little decomposition of organic matter. Any reduction of soil disturbance can be expected to reduce soil carbon losses.

Rock fragments

Tillage brings rocks to the surface that interfere with field operations, while no-till leaves the rocks where they are. An important advantage of no-till is the absence of rock picking.

Labor requirements

Elimination of soil tillage commonly reduces labor requirements by 50% per acre. The labor requirements for soil tillage are usually during a busy period of the year. In many cases, planting has to be delayed because of tillage. With no-till, crops can be planted in a timely fashion. This is especially relevant when double-cropping soybeans after wheat. A high percentage of double-cropped soybeans is therefore no-tilled.

Equipment and fuel

Tillage equipment costs money to buy and maintain. It is therefore cheaper to eliminate tillage. Extra attention has to be given to the planter in no-till, however. The planter needs to have adequate weight to be able to provide the downpressure needed to penetrate the soil. Coulters may be needed to prepare the seed zone. Fuel requirements of tillage are the highest of any field operation. Fuel savings with no-till are commonly 1.5–3 gallons per acre, compared to moldboard or chisel plowing and secondary tillage.

Box 1.1-6. Factors leading to gains and losses of organic matter in soils.

Factors promoting gains	*Factors promoting losses*
Cover crops	Soil erosion
Reduced tillage	Intensive tillage
Return of plant residues to soil	Whole plant removal
Low temperatures	High temperatures
Controlled grazing	Overgrazing
High soil moisture	Low soil moisture
Surface mulches	Fire
Application of compost and manure	Absence of organic additives
Appropriate fertilization	Excessive mineral nitrogen
High plant productivity	Low plant productivity
High plant root:shoot ratio	Low plant root:shoot ratio

Source: Brady and Weil, 1999.

No-Tillage Management Intensity Zones for Pennsylvania

No-till with maximum crop residue cover has many benefits. Adaptation of no-tillage crop production, however, has not been equally successful in all soils and climates. To give farmers direction as to the challenges they may encounter with no-till compared to other tillage systems, we developed no-till management intensity zones for Pennsylvania based on results from long-term experiments in the Midwest and Northeast regions of the United States. These zones were developed assuming continuous corn cultivation in which all crop residue is left in the field. When moving from Zone 1 to Zone 6, there are increasing challenges to no-till corn production. In the zones with more challenges, modifications to equipment or crop rotations may be necessary to obtain comparative yields with no-till as with conventional tillage systems. The map created is based on the available soils and climate information, and is generalized to accommodate the scale of the map. There will be many exceptions, because of local soil and climatic variations, that could not be captured in this map.

The classification we developed for the *Agronomy Guide* employs the following criteria:

- *Growing degree days (GDD).* If the area has less than 2,800 GDD for corn, it is less conducive to no-till because slow warming of soils in spring is likely to reduce yields. While slow early growth of no-till corn is also common in the areas with more than 2,800 GDD, this is not likely to result in differences in yield.
- *Drainage.* On soils that are less than moderately well drained, no-till and mulch till usually result in yield reductions compared to conventionally tilled corn. If more than 20% of the area consisted of hydric soils, the area is classified as having poor drainage.
- *Slope.* If more than 30% of the land has slopes exceeding 8%, the area is classified as having high erosion potential. On these soils, high-residue systems such as no-till and mulch till have an advantage because of erosion control.
- *Water-holding capacity of the root zone.* If the water-holding capacity of the root zone is less than 6 inches, high-residue tillage systems such as no-till and mulch till have an advantage over conventional tillage because of their ability to conserve water.

- *Rock fragment content.* When an abundance of rock fragments is present, an area is judged to be less suitable to tillage. No-till has an advantage on these soils. High rock fragment zones are those where more than 30% of the area was mapped as sandy skeletal or loamy skeletal soils.

Zone 1

Most soils in this region are highly conducive to no-till. The growing season exceeds 2,800 GDD for corn, and the soils are predominantly well drained. The lower soil temperatures in spring under no-till should not lead to yield reductions in this zone. Erosion is a serious threat on these soils, many of which have slopes exceeding 8%. No-till helps to maintain the crop residue cover to limit erosion. The water-holding capacity of these soils is low, and maintaining permanent crop residue cover helps conserve water. Many of the soils in this zone contain high amounts of rock fragments. No-till helps to avoid the need of extensive rock picking.

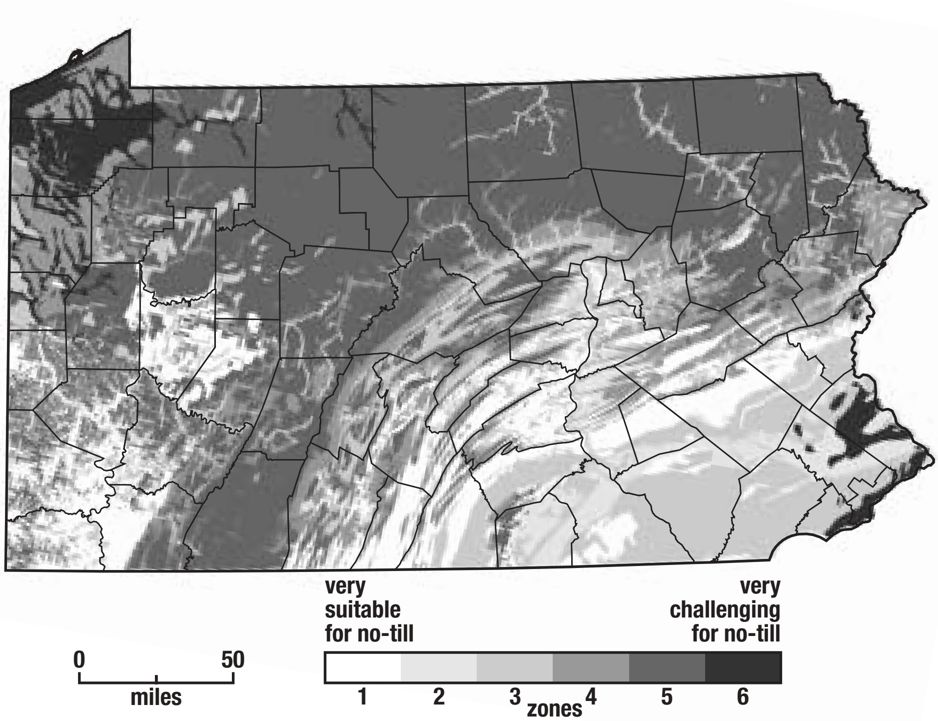
Zone 2

Most soils in this zone are very suitable for no-till. The growing season exceeds 2,800 GDD for corn, and soils are well drained. The lower soil temperatures in spring under no-till should not result in yield reductions in this zone. Erosion is not as serious a threat on these soils as in Zone 1. The water-holding capacity of these soils is low, and maintaining permanent crop residue cover helps conserve water. Many of the soils in this zone contain high amounts of rock fragments. No-till helps to avoid the need for extensive rock picking.

Zone 3

Most soils in this zone are very productive and have few constraints for any tillage system. The growing season has more than 2,800 GDD for corn, with the exception of some of the more northern areas and those at high elevation. The soils are commonly well drained. Slopes are mostly less than 8%, limiting the danger of erosion. Most of these soils have high water-holding capacity, so the moisture-conserving benefits of no-till are of moderate importance. Rock fragments are rare and pose no great problem to tillage. Adjustments to equipment and careful crop rotations can make no-till successful in those areas of this zone where the growing season has less than 2,800 GDD for corn. Row cleaners and/or use of zone tillage to clean the row when planting, enable quicker warm-up of soils with high residue cover. Rotating crops producing a lot of non-fragile crop residue (such as corn) with crops producing lower quantities of fragile residue (such as soybeans) is another way to obtain equal yields with either no-till or conventional tillage.

Figure 1.1-10. No-till management intensity zones for Pennsylvania.



Zone 4

This zone is located in the colder parts of the state with a growing season that has less than 2,800 GDD for corn. Cold soil temperatures are expected to depress early growth in no-till compared to a conventionally tilled corn. The soils are mostly well drained. The slopes are mostly less than 8% and have a reduced danger of soil erosion. However, these soils also have low water-holding capacity and tend to be droughty. Rock fragment content can be high in these soils. The moisture-conserving benefits of high residue cover should pay off and result in equal or higher yields for no-till crops compared with tilled crops. Row cleaning devices or rotations of high-residue with low-residue producing crops may help soils warm up faster in the spring in no-till.

Zone 5

This zone is in the colder parts of Pennsylvania with less than 2800 GDD for corn. The soils are mostly well-drained. Slopes are often greater than 8%, and the erosion potential is high. Crop residue cover should be maintained for soil conservation. The water-holding capacity of the soils in this zone is mostly high, so water conservation benefits due to no-till are not as crucial as in Zone 4. Rock fragment content can be high in these soils. Moving some residue prior to planting to enable warm-up of the soils in the spring while maintaining good residue cover for erosion control is recommended. Zone tillage seems to be a promising tillage system for this region. Row cleaners on the planter unit may help to improve soil warming in spring. Planting on the contour is recommended for erosion control.

Zone 6

This zone covers areas with both more and less than 2,800 GDD for corn. Most soils in this zone suffer from poor drainage. Slopes are generally less than 8%, and erosion potential is therefore moderate to low. The water-holding capacity is moderate to high. Rock fragment content is mostly low to moderate. These are the most challenging soils for high-residue tillage systems such as no-till and mulch till. The disadvantages of conventional tillage, such as erosion, water losses, and rock picking, are less pronounced when the soils are on relatively level land. It is possible to make conservation tillage successful in this zone, but extra effort is needed to achieve drying and warming of the soil. Zone tillage and row cleaners help to prepare a zone that is clean of residue in no-till. Rotation of high- and low-residue producing crops is an alternative means to boost yields on these soils with no-tillage.