SOIL AND WATER MANAGEMENT

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Soil is the central component of many ecosystem functions and services. Soil condition and management regulate these processes.
CONSEQUENCES OF MISMANAGEMENT
Erosion and deposition occur simultaneously across a landscape. (Left) The soil on this hilltop was worn down by water and tillage erosion during nearly 300 years of cultivation. The surface soil exposed on the hilltop consists mainly of light-colored C horizon material. At sites lower down the slope the surface horizon shows mainly darker-colored A and B horizon material, some of which has been deposited after eroding from locations upslope. (Right) Erosion on the sloping wheat field in the background has deposited a thick layer of sediment in the foreground, burying the plants at the foot of the hill.

(Photos courtesy of Ray R. Weil (left) and USDA Natural Resources Conservation Service (right))
Off-site damages caused by soil erosion include the effects of sediment on aquatic systems. A sediment-laden tributary stream empties into the relatively clear waters of a larger river. The turbid water will foul fish gills, inhibit submerged aquatic vegetation, and clog water-purification systems. Part of the sediment will settle out on the river bottom, covering fishspawning sites and raising the river bed enough to aggravate the severity of future flooding episodes. (Photos courtesy of USDA Natural Resources Conservation Service (left), NASA (middle), and Ray R. Weil (right))
Off-site damages caused by soil erosion include the effects of sediment on aquatic systems. A NASA satellite image shows the heavy sediment loads (yellow) entering the Chesapeake Bay on the US Atlantic coast from major tributary rivers such as the Potomac in the west and the Susquehanna in the north.

*(Photos courtesy of USDA Natural Resources Conservation Service (left), NASA (middle), and Ray R. Weil (right))*
Eutrophication process leading to hypoxia. From CAST (1999). For a detailed account of the causes and effects of the Gulf of Mexico dead zone, see Boesch et al. (2009).
The gulf hypoxia zone, areas in Red show excessively low levels of oxygen (hypoxia)
CRITICAL SOIL PROPERTIES AND FUNCTIONS
Soil is a three phase system consisting of solids, liquids and gas
Porosity defines the percentage of a soil that is made up of pores.
Figure 4.7 Classification of soil particles according to their size. The shaded scale in the center and the names on the drawings of particles follow the U.S. Department of Agriculture system, which is widely used throughout the world and in this book. The other two systems shown are also widely used by soil scientists and by highway construction engineers. The drawing illustrates the sizes of soil separates (note scale).

(Diagram courtesy of Ray R. Weil)
Coarse soils (sands) have much larger pores than fine textures (clay soils)

Fine- and coarse-textured soils at the same water potential but very different water contents. (Left) Sandy soil at -10 kPa potential in which particles are surrounded by water films of a uniform thickness. Most of the pore space is filled with air. (Right) Silty soil at -10 kPa potential with much smaller particle surrounded by uniform films of water of the same thickness as those in the sandy soil. However, the particles and pores are more numerous and smaller than in the sandy soil, so water films of the same thickness cause most of the porespace in the silty soil to be filled with water, not air. Because both soils have the same water potential they would feel similarly moist and could easily supply water to plants, but it is visually obvious that the silty soil has a much greater water content than the sandy soil.

(Diagram courtesy of Ray R. Weil)
The potential rate of water entry into the soil, or infiltration capacity, can be measured by recording the drop in water level in a double ring infiltrometer (top). Changes in the infiltration rate of several soils during a period of water application by rainfall or irrigation are shown (bottom). Generally, water enters a dry soil rapidly at first, but its infiltration rate slows as the soil becomes saturated. The decline is least for very sandy soils with macropores that do not depend on stable structure or clay shrinkage. In contrast, a soil high in expansive clays may have a very high initial infiltration rate when large cracks are open, but a very low infiltration rate once the clays swell with water and close the cracks. Most soils fall between these extremes, exhibiting a pattern similar to that shown for the silt loam soil. The dashed arrow indicates the level of $K_{sat}$ for the silt loam illustrated.

*Diagram courtesy of Ray R. Weil*
Macropores
Macropores are regular infiltration; the blue dye was applied to the surface and infiltrated into the soil mainly via macropores.
**Figure 6.14** Influence of soil structure and vegetation on the partitioning of rainfall into infiltration and runoff. The upper two diagrams show soils with tight, unstable, or compacted structure that resists infiltration and percolation. The bare soil is especially prone to surface sealing and resulting high losses by runoff. Even with forest cover, the low-permeability soils cannot accept all the rain in an intense storm. The two lower diagrams show much greater infiltration into soils that have open, stable structures with significant macropore space. The more open soil structure combined with the protective effects of the forest floor and tree canopy nearly eliminate surface runoff.

*(Diagram courtesy of N. C. Brady)*
Slope impacts infiltration, greater slope = less infiltration and more runoff. Whatever water does not infiltrate, moves downhill as runoff. Runoff can transport nutrients and cause erosion.

Managing soil hydrology often means increasing infiltration (via cultural practices, e.g. cover crops, conservation tillage) in order to minimize runoff (bad)
Factors Influencing Infiltration

- Soil Texture
  - Sandy
  - Clayey

  High Infiltration  Low Infiltration

- Porosity (greater porosity = more infiltration)
  - Porosity is influenced by compaction

- Slope (Higher Slope = less infiltration)
Cartoon on the left = compacted soil, decreased porosity

Cartoon on the right = compacted soil, decreased porosity
Figure 5.15  Effect of compaction on volumetric water content $\Theta_v$ for soils with a given mass water content. Compaction of two forest soils decreased total porosity mainly by converting the largest (usually air-filled) pores into smaller pores that hold water more tightly. These forested A horizon soils were initially so loose that the moderate compaction benefited plants by increasing the volume of water-holding 0.2–30 $\mu$m pores. On the other hand, the water originally in the uncompacted soil takes up a greater proportion of the pore volume (indicated as $\text{cm water/cm soil}$) when the soil is compacted, possibly leading to nearly water-saturated conditions. For example, here the clay loam with severe compaction contains 0.52 cm$^3$ water, but only 0.04 cm$^3$ air per cm$^3$ soil, less than the 0.10 cm$^3$ air per cm$^3$ soil ($\approx$ 10% air porosity; see Section 7.2) thought to be required for good plant growth. This figure is worth careful study to understand the relationships among mass and volume water contents, bulk density and porosity. 

[Adapted from Shestak and Busse (2005) with permission of The Soil Science Society of America]
Platy compacted structure
Compacted soil structure in a pit
Vehicle traffic is a leading cause of compaction.

Increased vehicle load = increased compaction pressure.

At the same load, proper tire inflation dissipates the force over larger areas keeping compaction effects near the surface.
Compaction impacts soil strength y-axis. Dense compacted soil (maroon line) has a higher strength leading to poor root penetration.

Water content impacts soil strength: Wetter soils have less strength and are more susceptible to compaction.
Soil strength and density (which are related) change with depth and management.

In tillage systems (conventional till, CT vs. no till, NT) density in the soil is increased (compaction) increasing soil strength and restricting root/crop growth.
Compaction susceptibility (vertical axis) is influenced by soil moisture and organic matter.

High OM soils are more resistant to compaction
Figure 4.35  The interaction of soil organic matter with the clay fraction accounts for most of the aggregate stability of such moderately weathered soils as the Duroc series. Consequently, the stability of soil aggregates declines when cultivation, especially with conventional tillage, decreases soil organic matter levels. In more highly weathered soils such as the Maury series, aggregate stability is less dependent on organic matter levels than on the interaction of iron oxide compounds with silicate clays such as kaolinite. The tillage system used therefore has less effect on aggregate stability in these more highly weathered soils. This Figure suggests that cultivated soils of the highly weathered tropics may have greater aggregate stability than their counterparts in temperate zones.

[Redrawn from Six et al. (2000)]
Alfalfa roots breaking up compacted layers
Factors influencing compaction

- Moist soil is weaker and more susceptible to compaction
- High OM soils are less susceptible
- High tillage increases compaction susceptibility
- Heavy vehicle traffic increases compaction
  - High volume tires (and tracks) keep compaction shallow
WATER QUALITY
Offsite (i.e. detrimental) movement of Ag. Chemicals (fertilizer, pesticides, manure) can take many forms. The two most important processes are runoff (overland flow) and leaching (sub surface flow)

Runoff and leaching can both contribute to the impairment of water
Importance of each mechanism depends on:

- Chemical Type
- Application Timing
- Application method
- Landscape (soil, slope, infiltration, conservation practice, etc.)
Ex. Nitrogen is highly mobile and leaches very easily, it can also volatize as NH4 of Nox. P is less mobile and leaches less readily, no volatization

Figure 16.5  Nitrogen moves from land to streams mainly dissolved in drainage water, while phosphorus is carried mainly in surface runoff. Therefore control of P loading usually focuses on reduced runoff and erosion, while control of N loading usually focuses on reduced leaching. Some nitrogen leaves the soil in gaseous forms that may be deposited in water from the atmosphere.

*Diagram courtesy of Ray R. Weil*
Nutrient runoff have a continental-scale impact
Right source: appropriate chemical/product

Right time: agronomic and environmental optimum applications

Right place: e.g. near the crop, in low runoff locations

Right: rate appropriate amount
Historically, we (agronomists) have over-applied N and P fertilizer

**Figure 16.3** Past and projected agriculture inputs and outputs of nitrogen and phosphorus. The surplus of N or P is the total for all inputs minus harvest (intentional removals such as crops and animal products). Projections for 2050 assume “business as usual.” If better nutrient management is widely adapted, future surpluses could be smaller than shown. (Right) Total P input includes both mineral and manure forms. Surplus P goes to accumulation in soils and runoff losses. (Left) Individual N inputs are shown, but for a breakdown of N surplus, see Figure 16.4. Note that the magnitudes for N fluxes are almost ten times greater than for P. Compare to N trends in Figure 13.18.

[Graphed from data in Bouwman et al. (2013)]
Winter application (i.e. frozen ground) applications of manure lead to high N and P loss (frozen soils = poor infiltration = large runoff events)

Incorporation can minimize runoff losses

**Figure 16.27** No-till injection of dry poultry manure greatly reduces nutrient losses as compared to broadcast application. (a) Phosphorus concentrations in surface runoff from pasture watersheds treated with poultry manure applied by surface broadcasting or by subsurface injection. Runoff P was equally low from both side-by-side watersheds before any poultry manure was applied (green circle at left). Most of the P losses occurred with the first runoff-producing rain after each manure application (thick blue vertical arrows indicate the large difference in P concentration between application methods). (b) Nitrogen loss to the atmosphere as ammonia gas occurred mainly during the first few days (but not nights) after application. The ammonia loss was also much greater when manure was broadcast than when it was
incorporated by disk tillage (22% as much loss) or by no-till injection (12% as much loss). (c) The photo shows an experimental manure applicator being developed by US Department of Agriculture researchers to inject dry poultry manure into the soil without disturbing the soil residue cover. [Redrawn from Pote et al. (2011) and Pote and Meisinger (2014); (c) USDA/ARS]
SOIL EROSION
Soil erosion degrades soil by removing topsoil and exposing (low fertility) B horizons

**Figure 17.50** The exposure of B horizon soil on the crests of small hills in cultivated landscapes is largely due to tillage erosion. (Left) The whitish calcareous subsoil material from Mollisols is mixed into the plow layer of a conventionally tilled field in sub-humid Minnesota. (Right) Reddish B horizon material is likewise mixed into the hilltop plow layer of Ultisols in a strip-cropped field in humid Virginia. The diagram illustrates how tillage scalps the hilltops by throwing soil farther downslope than upslope, resulting in a net movement of soil downslope and gradual leveling of the landscape. 

*(Diagram courtesy of Ray R. Weil. Photos courtesy of Ray R. Weil (right) and David A. Lobb, University of Manitoba (left))
We can manage all processes in the erosion cycle.

Detachment: protect the soil (cover crops, crop residue, crop canopy)

Transport: Contour strips, tillage direction, etc.

Deposition: filter and buffer strips

**Figure 17.9** The three-step process of soil erosion by water begins with the impact of raindrops on wet soil. (a) A raindrop speeding toward the ground. (US Navy) (b) The splash that results when the drop strikes a wet, bare soil. Raindrop impact destroys soil aggregates, encouraging sheet and interrill erosion. Also, considerable soil may be moved by the splashing process itself. The raindrop affects the detachment of soil particles, which are then transported and eventually deposited in locations downhill (c).

*(Diagram courtesy of Ray R. Weil; (b) US Navy)*
Figure 17.15 The importance of vegetative cover on soils. Immediately after a heavy rainstorm, runoff (left) is scouring a gully and carrying off a heavy sediment load from a cultivated soil with almost no residue cover while (right) on a soil with almost 100% cover the runoff is clear.

(Photos courtesy of Ray R. Weil)
Erosion vs. Sedimentation

Erosion = movement of soil (via wind or water)

Sedimentation = impairment of water bodies by excess sediment additions
Figure 16.13  Landscape management to moderate runoff and retain nutrients. (a) With no practices, nutrient and sediment laden runoff flows rapidly to stream. (b) A riparian buffer zone slows the runoff and removes some nutrients. (c) Waterway check dams and contour buffers in the tilled crop field slow and partially clean runoff water before it reaches the riparian buffer. (d) Best results are obtained where the landscape management integrates many practices: conservation tillage and cover crops in the fields, buffers in the waterways, retention wetlands, and riparian buffer zones.

[For more on these concepts, see Kröger et al. (2013)]
Figure 16.8 A multispecies riparian buffer strip designed to protect the stream from nutrients and sediment in cropland runoff while also providing wildlife habitat. A grass-covered level berm spreads runoff water evenly to avoid gullies. Perennial grasses filter out sediments and take up dissolved nutrients. Deep tree roots remove nutrients from shallow groundwater. Soluble carbon from tree litter percolates downward to provide energy for anaerobic denitrifying bacteria that remove additional nitrogen from groundwater. Woody vegetation provides wildlife habitat, shade to cool the stream, and woody debris for fish habitat. A total buffer width of 10–20 m can usually provide most of these potential benefits.

(Diagram courtesy Ray R. Weil)
Figure 17.20  Practices supporting erosion control. (Left) Contour cropping with graded terraces between crop strips and grassed waterway to safely convey off excess water off a sloping field in Kansas. The broken arrows show paths taken by the runoff water. (Right) Contour strip-cropping with alternating strips of mature wheat and young green alfalfa on a farm in New York. The arrow indicates a grassed waterway.
(Photos courtesy of Jeff Vanuga, USDA/NRCS (left) and Ray R. Weil (right))
Figure 16.9  Effectiveness of perennial herbaceous (prairie) vegetation filters for reducing nutrient loss from cropland. A diverse mixture of native prairie forbs and grasses was seeded in portions of a crop field (shown in green), either in 3–6 m wide contour strips or in the bottom of the watershed. The three practices shown all reduced nutrient losses by >80%, but planting prairie vegetation in only the bottom 10% of a field proved to be the most convenient and economical practice to implement. The soils were Hapludalfs and Argiudolls with 6–10% slopes. A no-till soybean–corn rotation was grown with 135–185 kg N ha$^{-1}$ and 50 kg P ha$^{-1}$ applied to the corn crops. Despite initial concerns, the prairie vegetation did not contribute weeds to any of the fields.

[Data and concepts selected from Zhou et al. (2014)]
Figure 17.21  Concentrated runoff erodes soil and carries away sediments on an unprotected, conventionally tilled crop field, despite planting across the slope (left). Water runs clear without scouring soil from a crop field protected by a permanent grassed waterway (right).  
(Photos courtesy of USDA/NRCS)
Figure 6.24  Cover crops and new mechanical weed control implements can help minimizing vapor losses of water from row-crop soil while planting the crop without tillage and without herbicides. (a) Mechanical termination of a rye cover crop using a rollercrimper mounted on the front of the tractor to avoid leaving rye unkillled in the tire tracks. A no-till planter mounted on the rear of the tractor is simultaneously sowing soybean seed into the freshly rolled and crimped cover crop residue mulch. (b) The resulting thick mulch of killed rye residue all but eliminates evaporation losses of water from the soil between soybean rows and suppresses most weed growth early in the season. The weeds that eventually did emerge through the mulch can be killed using a high residue cultivator that slices and lifts the soil under the mulch while leaving the surface mulch largely undisturbed. (c) The high residue cultivator works by cutting a slit through the mulch with sharp rolling coulters followed by a V-shaped sweep that slices and lifts the soil under the mulch to destroy the roots of young weeds growing between the soybean rows. This technology is of particular relevance to organic farming in which use of synthetic weed killing chemicals is not allowed.

(Photo © Rodale Institute)
Figure 16.10  Cover crops can capture soluble nitrogen (e.g., NO$_3$-N) left in the soil profile after the main cropping season, thus substantially reducing N loss to groundwater during the winter. Forage radish and rye (photo) are cover crops capable of capturing > 100 kg/ha of such residual N in fall, cleaning the soil profile of soluble N to considerable depths. The graph shows nitrate-N in November, expressed as kg N/ha for each 15 cm depth increment of this sandy Ultisol. The control plots had some weeds, but no cover crop.

[Data from Dean and Weil (2009); photo courtesy of Ray R. Weil]
Minimizing soil disturbance through conservation or reduced tillage can have many benefits (increased infiltration, reduced runoff and erosion, etc.)

**Figure 17.22**  Conventional inversion tillage and conservation tillage in action. (Left) In conventional tillage, a moldboard plow inverts the upper soil horizon, burying all plant residues and producing a bare soil surface. (Right) A chisel plow, one type of conservation tillage implement, stirs the soil but leaves a good deal of the crop residues on the soil surface. *(Photos courtesy of Ray R. Weil)*
Crop residue protects soil (less evaporation, less detachment)

**Figure 6.28b** Conservation tillage leaves plant residues on the soil surface, reducing both evaporation losses and erosion. No-till planted corn in a more humid region grows up through the residues left on the surface by previous corn, soybean and wheat crops. Note that with no-till, virtually none of the soil surface is directly exposed to solar radiation, rain, or wind. Weeds are normally controlled with herbicide sprays.

*(Photos courtesy of Ray R. Weil)*
Impact of residue cover on erosion process (aka why conservation tillage works)

**Figure 17.17** Reduction in interrill erosion achieved by increasing ground cover percentage. The diagrams above the graph illustrate 5%, 20%, 40%, 60%, and 80% ground cover. Note that even a light covering of mulch has a major effect on soil erosion. The graph applies to interrill erosion. On steep slopes, some rill erosion may occur even if the soil is well covered. Generalized relationship based on results from many studies.  
* (Diagram courtesy of Ray R. Weil)
Cultivation direction impacts runoff water volume and erosion rates

**Figure 17.18** Erosion and water runoff losses from small watersheds where potato (a row crop with high soil disturbance) was grown either up and down the slope, or on the contour in a system with diversion terraces and a grassed waterway. The contour practices provided dramatic soil and water conservation benefits. Data are annual rates averaged across three years. *From Chow et al. (1999)*
Figure 17.26  Short-term effect of tillage systems on soil erosion and runoff from corn plots in Illinois following corn and following soybeans. Soil loss by erosion was dramatically reduced by the conservation tillage practices. The period of runoff was reduced most in this short-term study by the disk chisel system where corn was grown after corn. The soil was a Typic Argiudoll (Catlin silt loam), 5% slope, planted up- and downslope, tested in early spring. [Data from Oschwald and Siemens (1976)]
Figure 17.27  The comparative effects of 49 years of three tillage systems on soil organic matter content (0–30 cm), soil physical soil properties (0–10 or 0–20 cm), and corn yields averaged across two fine-textured soils in Ohio (a Fragiudalf and an Epiaqualf) growing continuous corn and corn–soybean rotations without cover crops. Values for the no-till system were taken as 100, and the others are shown in comparison. Bulk density (0–10 cm) and corn yields (five-year average) were about the same for each tillage system, but for all other properties the no-till system was decidedly more beneficial than either of the other two systems. No-till management had especially large impacts on saturated hydraulic conductivity (0–10 cm), available water holding capacity (0–20 cm), and macroaggregation (>2 mm).

[Graphed from data in Kumar et al. (2012a) and Kumar et al. (2012b)]