Chapter 2

Soil Health

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Abstract

Soil health refers to a balanced condition of soil physical, chemical, and biological processes conducive to high productivity and environmental quality. Soil health concepts are commonly used to evaluate changes, compare soils, or assess the effectiveness of land-use management. This chapter deals with soil health concepts, soil health indicators and their assessment, current understanding of management effects on soil health, and guidelines for improving soil health and sustainable crop production in the inland Pacific Northwest (PNW). Intensive agricultural systems within the inland PNW have depleted more than 50% of native soil organic matter (SOM), deteriorated soil microbial community, faunal diversity, and soil structure, and increased soil erosion. Crop residue incorporation into soil with intensive tillage, residue burning and removal, little biomass production and return from the dominant cereal-fallow cropping system, lack of crop diversity, farming on steep slopes, continuous application of ammonium-based nitrogen fertilizers, and limited and untimely precipitation are the major factors contributing to the deterioration of soil health and reduced agronomic productivity within the inland PNW. However, through sustained research and extension activities there is evidence that soil health can be improved by adopting practices such

Research results are coded by agroecological class, defined in the glossary, as follows:

● Annual Crop ▲ Annual Crop-Fallow Transition ■ Grain-Fallow as conservation tillage systems, residue retention, no residue burning, cropping rotation and diversification, annual cropping, balanced and efficient nutrient management, organic soil amendments, reducing acidity, and integrated nutrient, pest, and weed management.

Key Points

- Soil health is vital for sustainable agricultural production and environmental quality.
- Soil health is assessed by evaluating the soil's ability to perform desired ecosystem functions and involves measuring soil physical, chemical, and biological indicators in response to changes in management.
- Soil's high degree of spatial variability poses challenges for the selection of indicators sensitive to management in soil health assessment programs.
- Site-specific adaptive management decisions can lead to long-term sustainability of soil health.
- Reduced tillage practices, cropping intensification and diversification, crop residue retention, and application of organic amendments can enhance soil health.

Soil Health: Concept and Background

Soil is a vital natural resource and its health is fundamental for sustainable agricultural production. **Soil health**, also referred to as soil quality, is defined as "the capacity of soil to function within ecosystem boundaries to sustain biological activity, maintain environmental quality, and promote plant and animal health" (Doran and Zeiss 2000). Soils function to provide ecosystem services that include increased soil water retention and availability, soil aggregation, nutrient cycling and storage, and microbial diversity and function.

Soil health assessment implies the evaluation of fitness of soil to perform desired functions and its capacity to resist and recover from degradation. Land managers, growers, and researchers assign a relative value to soil health using various qualitative and quantitative indicators. For instance, soil **compaction** leads to loss of **soil structure**, limited water and air **infiltration**, and poor root development, rendering soil less productive than a non-compacted, well-structured soil. Here, the suitability of soil for proper root growth (soil function) can be judged by determining soil **bulk density** and penetration resistance (soil health indicators) using appropriate tools. Growing deep-rooted **cover crops** may help reverse soil compaction. A healthy soil should possess the following characteristics:

- High organic matter
- Good soil tilth and structure
- High water infiltration and retention
- Resistance to compaction
- High soil biological activity
- Plant nutrient recycling and availability
- Resistance to erosion
- Devoid of toxic chemicals
- Low in weed and disease pressures

Indicators of Soil Health

Soil health indicators generally describe specific soil properties. Soil properties can be generally categorized as stable or dynamic. Stable soil properties are influenced by soil-forming factors such as climate, organisms, parent material, and topography, which change little with management practices. Examples of stable properties include soil texture, soil type, and soil depth. Dynamic properties can change with land-use and management practices over the course of a short time, generally within a human lifespan, and include SOM, bulk density, and **pH**. Accordingly, soil health assessment programs that include measurement of various physical, chemical, and biological properties of soil that respond to management changes provide clues on soil processes. However, there is no consensus on soil health indicators that are applicable to every agroecosystem. Soil health indicators are site-specific and sometimes temporal in nature. For instance, increased soil water storage would be a desirable indicator in the Palouse region of the **inland PNW** where precipitation is limited, whereas excess water-causing anaerobic conditions are a bad indicator in the west coast areas of the PNW with too much precipitation. Some of the commonly used soil properties to assess soil health are listed in Table 2-1.

Table 2-1. Potential physical, chemical, and biological properties used in soil health assessment.

Physical	Chemical	Biological
✓ Soil color ✓ Aggregate stability ✓ Water infiltration ✓ Bulk density ✓ Penetration resistance ✓ Water holding capacity ✓ Runoff and erosion ✓ Rooting depth	✓ Organic C and N ✓ Particulate organic matter ✓ Active carbon ✓ pH ✓ Cation exchange capacity and base saturation ✓ Electric conductivity ✓ Heavy metals	✓ Soil respiration ✓ Potential mineralizable nitrogen ✓ Microbial biomass ✓ Soil enzymes ✓ Earthworms ✓ Crop condition, root growth ✓ Weed and disease pressure

Visual Indicators

Farmers often describe soil health based on their perception of its look, feel, smell, and taste. Such visual and morphological observations of soil physical condition and plant growth can track status of soil health. Often, these observations guide subsequent soil health assessments. Changes in soil color, soil crust formation, ephemeral gullies, runoff, physical structure and aggregation, soil depth, root growth, crop emergence, and weed density are some potential visual indicators. For instance, SOM content usually decreases with depth, and is observed as dark-colored soil in top soil horizons that progressively lightens with depth (Figure 2-1). Rills and gullies formed shortly after a rain indicate runoff and slow water infiltration into soil. Soil crusting, reduced aggregation, and surface sealing indicate surface compaction and loss of SOM. Uniform crop emergence and good growth indicate good soil health and management. Deep soils promote SOM, nutrients, water storage, and root growth.

Aggregate Stability

Soil **aggregates** or clods are groups of primary soil particles that are held together by organic (fungal hyphae, bacterial mucilage, root exudates, polysaccharides, lipids, etc.) and inorganic materials (clay, polyvalent

Figure 2-1. A darker color of the surface soil (left) indicates the presence of higher organic matter content compared to the subsoil (right). (Photo by Rakesh Awale.)

metal cations such as calcium and iron, oxides and hydroxides of iron and aluminum, calcium and magnesium carbonates, etc.). **Aggregate stability** refers to the capability of soil aggregates to resist disintegration when exposed to external destructive forces from tillage, water, wind, and freeze-thaw cycles. Soil aggregate stability can be determined by measuring the proportion of aggregates in different size classes, percentage of the stable aggregates (in a specified size class) upon wet or dry sieving, and distribution of stable aggregates into different size ranges.

Generally, high soil aggregate stability and greater amounts of stable aggregates are desirable for sustaining agricultural productivity and protecting environmental quality. Stable aggregates favor high water infiltration rates, provide adequate aeration, resist soil erosion by wind and water, and enhance root growth (Figure 2-2). Stable soil aggregates also provide physical protection of SOM from microbial decomposition, particularly when the proportion of large (>0.25 mm diameter) aggregates increases. Conversely, disintegration of aggregates leads to the formation of surface crusts and result in more runoff, more erosion, and less available water (Figure 2-2). In the Grain-Fallow **agroecological class** (AEC), disking, rodweeding, and packing operations under disk tillage winter wheat-fallow (WW-F) systems reduced the proportion of non-erodible soil aggregates and mean aggregate diameter compared to low disturbance **no-till** spring wheat-chemical fallow (SW-ChF) system (Table 2-2) ■. Consequently, soil water content and **matric potential** (a measure of soil water) were lower, and the susceptibility of soils to wind erosion was higher with disk tillage WW-F than no-till SW-ChF ■. Similarly, in the Annual Crop AEC, no-till increased the proportion of dry aggregates of size above 1 mm, whereas conventional tillage had

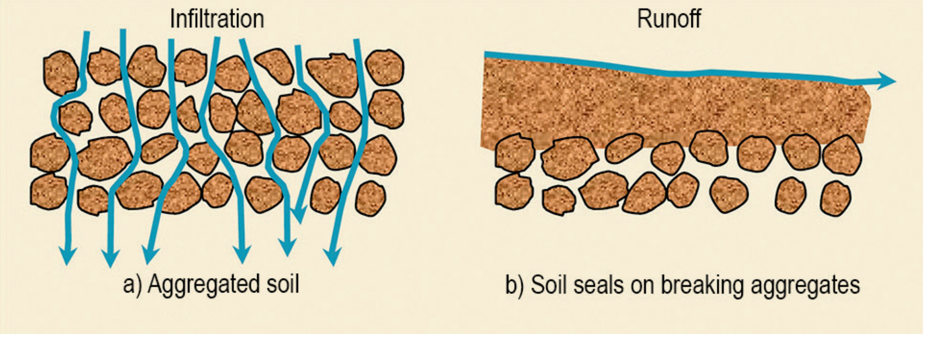

Figure 2-2. Water flow patterns in well-aggregated and weakly aggregated soils. (Reprinted from Magdoff and Van Es 2009.)

Table 2-2. Soil aggregate parameters, water content and susceptibility to wind erosion under no-till spring wheat-chemical fallow (NT SW-ChF) and disk tillage winter wheat-fallow (DT WW-F) cropping systems in east-central Washington. ■

Cropping system	Non-erodible aggregates (%)	Aggregate mean diameter (inch)	Water content (%)	Matric potential (Mpa)	SLR index
NT SW-ChF	50.0	0.09	1.7	−197.8	0.067
DT WW-F	38.8	0.01	1.4	−284.5	0.174

SLR: soil loss ratio, an indicator of wind erosion with 0 = no erosion and 1 = maximum erosion potential.
Adapted from Feng et al. 2011a.

greater proportion of soil aggregates of size below 0.25 mm (Kennedy and Schillinger 2006) ●. See Chapter 1: Climate Considerations for more information on AECs.

The addition of organic materials and retention of crop residues promotes stable soil aggregation by enhancing soil biological activity and the production of various binding agents (such as fungal hyphae, polysaccharides, mucilage, and lipids) and by protecting the aggregates from direct physical impacts of raindrops and wind. A study in the Annual Crop-Fallow Transition AEC revealed that water stability of 1–2 mm soil aggregates as well as that for whole soil was higher with the application of organic manure and pea vines than when synthetic N fertilizers were applied (Table 2-3) ▲. Organic amendments increased the amounts of glomalin (fungal glycoprotein) that act as an insoluble glue to stabilize soil

Table 2-3. Addition of organic materials enhances soil aggregate stability, water movement, and soil biological activity in a winter wheat-fallow (WW-F) rotation under conventional tillage near Pendleton, Oregon. ▲

Soil parameters	Organic amendments		Synthetic N fertilizer	No fertilizer
	Manure	Pea vines		
	100 lb N/ac	30 lb N/ac	80 lb N/ac	0 lb N/ac
Total C (%)	1.590	1.260	1.170	1.090
Total N (%)	0.135	0.103	0.092	0.088
Water stability				
Whole soil (proportion)	0.48	0.41	0.35	0.30
1–2 mm aggregates (proportion)	0.83	0.69	0.65	0.56
Percolation (cubic inch/hr)	1.06	0.95	0.84	0.73
Ponded infiltration (inch/hr)	5.53	4.09	1.49	1.46
Total glomalin (%)	0.259	0.235	0.214	0.213
Earthworm count (per square meter)	128	144	72	80

Adapted from Wuest et al. 2005.

aggregates. Consequently, soil water infiltration rates were higher in soils treated with organic material compared to a synthetic fertilizer addition ▲.

Bulk Density and Compaction

Bulk density is the ratio of the mass of oven-dry soil to its bulk volume. It is a measure of soil compaction. Soil compaction occurs when soil particles are pressed together reducing porosity (pore space) between them. Soil compaction (high bulk density) restricts plant root growth by increasing resistance to root penetration (impedance) (Figure 2-3) resulting in reduced nutrient uptake, nutrient deficiencies, and crop yield. Compaction of soil also reduces air and water permeability resulting in reduced soil water infiltration and increased runoff and soil erosion.

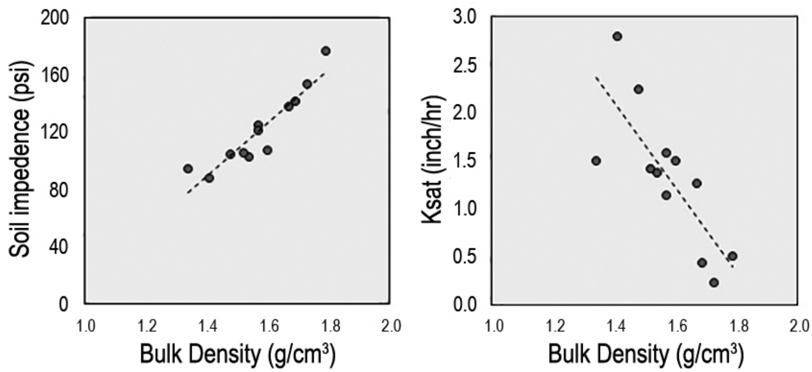

Figure 2-3. Relationships of soil bulk density, impedance (compaction), and saturated hydraulic conductivity (Ksat) within the surface 2 feet of soil after a one-time, high-axle load traffic pass (<5, 10, and 20 ton loads) under winter wheat-spring barley-spring pea (WW-SB-SP) rotation near Moscow, Idaho. (Adapted from Hammel 1994.) ●

The most yield-limiting soil compaction is caused by wheel traffic from heavy equipment. In the Annual AEC, soil compaction under a 20-tons-per-axle load resulted in a 14% yield reduction in spring barley compared to the 5-tons-per-axle load due to water stress and restricted root growth (Figure 2-4) ●. The potential for wheel traffic compaction increases on wet soils because soil water lubricates soil particles, making them easier to move against each other. Therefore, avoiding field operations on wet soils, limiting axle load, and decreasing traffic area can minimize wheel traffic soil compaction.

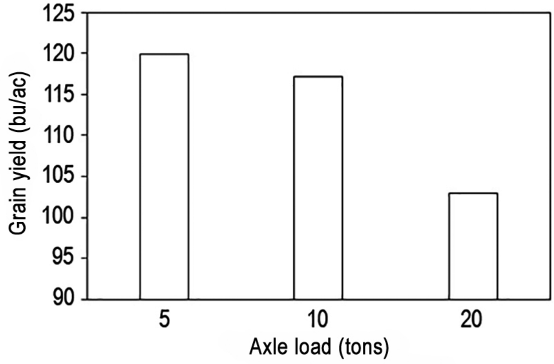

Figure 2-4. Effect of soil compaction from three axle loads on yield of spring barley in a winter wheat-spring barley-spring pea (WW-SB-SP) rotation near Moscow, Idaho. (Adapted from Hammel 1994.) ●

Intensive tillage practices can also increase the susceptibility of a soil to compaction by reducing aggregate stability. For instance, in the Grain-Fallow AEC, greater soil disturbance from disking and packing prior to seeding wheat in late summer increased bulk density under disk tillage WW-F compared to low disturbance systems such as no-till spring wheat-spring barley (SW-SB) and no-till SW-ChF rotations (Table 2-4) ■. Often, a compacted soil layer is formed below the tillage zone due to a continuous smearing action of the tillage implement. In the Grain-Fallow AEC, no soil compaction was seen under either chisel tillage or no-till systems in the top 9 inches of soil, but the plots under chisel tillage were more compacted than no-till plots between 10- to 16-inch depths (Figure 2-5) ■.

Soil bulk density decreases with an increase in SOM content (Figure 2-6) ●. Therefore, management practices which add organic materials such

Table 2-4. Bulk density of no-till spring barley-spring wheat (NT SB-SW), no-till spring wheat-chemical fallow (NT SW-ChF), and disk tillage winter wheat-fallow (DT WW-F) cropping systems in east-central Washington. ■

Cropping system	Bulk density (g/cm^3)	
	Spring	Late summer
NT SB-SW	0.87	0.85
NT SW-ChF	1.03	0.95
DT WW-F	0.98	1.04

Adapted from Feng et al. 2011b.

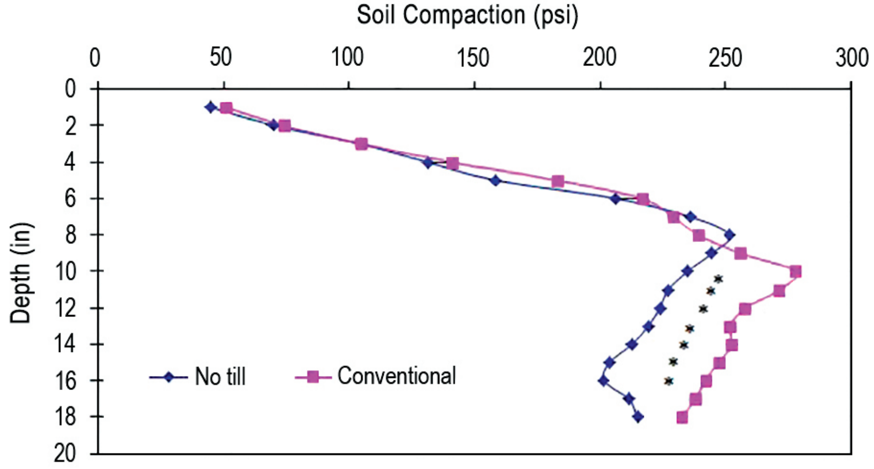

Figure 2-5. Subsoil compaction under chisel tillage in winter wheat-fallow (WW-F) near Wilbur, Washington. (Reprinted from Esser and Jones 2013.)

as manure, compost, and crop residues can reduce soil compaction. For instance, annual cropping of SB-SW reduced soil bulk density over grain-fallow rotations (SW-ChF or WW-F) because annual cropping likely increased SOM content from greater crop residue input (Table 2-4). Including cover crops in cropping systems and rotation with deep-rooted crops favors soil aggregation and could offset compaction.

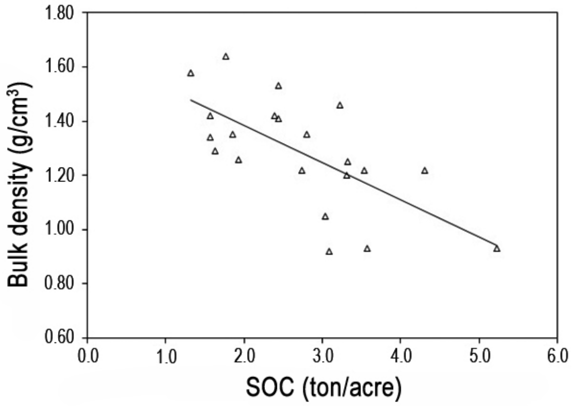

Figure 2-6. Relationship of soil organic carbon (SOC) and bulk density within 0 to 8 inches of Palouse silt loam managed across native prairie, perennial vegetation, no-till, and conventional tillage systems in eastern Washington. (Adapted from Purakayastha et al. 2008.)

Soil Water Dynamics: Infiltration, Hydraulic Conductivity, and Water Content

Soil water is the most limiting factor in crop production in the inland PNW. Soil infiltration, **hydraulic conductivity**, water content, and water-holding capacity provide information on soil water movement and plant available water. Soil infiltration is a measure of the rate of water entry into soil and hydraulic conductivity refers to the rate of water movement through soil. Soil hydraulic properties are directly related to soil aggregate stability, compaction, porosity, and pore continuity. Ultimately, these properties regulate soil water storage, nutrient transport, and soil erosion.

Soil type and structure, tillage, SOM content, residue cover, and initial water content influence soil hydraulic properties. Table 2-5 shows that annual cropping increases both water infiltration and saturated hydraulic conductivity in soil compared to a grain-fallow rotation. This is attributed to increased SOM accumulation due to annual residue inputs, increased soil aggregation, and reduced bulk density ■.

Soil disturbances with tillage may temporarily enhance soil water infiltration and conductivity by loosening soils and opening channels. However, tillage also degrades soil structure, breaks pore continuity, and

Table 2-5. Cumulative infiltration and saturated hydraulic conductivity of soil measured under three cropping systems in east-central Washington. ■

Season (time of measurement)	Cropping system†	Cumulative infiltration (in/hr)	Hydraulic conductivity (in/hr)
Spring (April)	NT SB-SW	2.6	21.8
	NT SW-ChF	1.4	5.4
	DT WW-F	2.3	26.6
Late Summer (September)	NT SB-SW	3.9	52.6
	NT SW-ChF	2.4	23.0
	DT WW-F	2.3	4.8

†Cropping systems are no-till spring barley-spring wheat (NT SB-SW), no-till spring wheat-chemical fallow (NT SW-ChF), and disk tillage winter wheat-fallow (DT WW-F). Adapted from Feng et al. 2011b.

creates surface crusts by sealing pores, which eventually reduces hydraulic conductivity and water infiltration. For instance, disk tillage WW-F increased infiltration and conductivity compared to no-till WW-ChF in spring. However, the effect was short-lived and both water infiltration and hydraulic conductivity were higher under no-till than under disk tillage plots in late summer (Table 2-5) ■.

Surface residues enhance soil aggregation, facilitate water infiltration, and prevent surface soil sealing caused by rain impact. No-till annual cropping systems result in increased ground cover that reduces surface runoff and soil erosion by providing greater time for water to infiltrate the soil (Table 2-6) ▲. Surface residues also reduce evaporative loss of soil water and increase plant available water by shielding soil from solar radiation and reducing air movement just above the soil surface (Donk and Klocke 2012). Therefore, evaporation rates are generally lower under residue-covered soil than under bare soil following a precipitation event.

Seasonal variations in soil hydraulic properties occur throughout the growing season in response to root development, earthworm activity, soil disturbances associated with tillage and seeding operations, and changes in precipitation and temperature. For instance, soil infiltration and saturated hydraulic conductivity both increased from spring to late summer, particularly under no-till systems, due to soil fracturing associated with seeding operations under no-till SW-ChF and wheat root growth under no-till SW-SB, as well as due to drier soil in late summer than in spring (Table 2-5) ■. In the Annual AEC, over-winter soil water storage (September to April) and soil water infiltration (measured after

Table 2-6. Mean annual ground cover, runoff, and soil erosion measured for two tillage systems near Pendleton, Oregon. ▲

Tillage	Cropping systems†	Ground cover	Runoff	Soil erosion
		%	inches	ton/ac
No-till	WW-ChF-WW-CP/SP	73	1.46	0.10
Conventional	WW-F	44	3.15	4.90

†Cropping systems are winter wheat (WW); chemical fallow (ChF); chickpea (CP); spring pea (SP); summer fallow (F).
Adapted from Williams et al. 2014.

crop harvest) remained similar between no-till and conventional tillage sites due to reestablishment of capillary pore continuity from the surface to below the tillage depth by vigorous and extensive growth of wheat roots during the crop-growing season (Kennedy and Schillinger 2006) ●.

Soil pH

Soil pH is a measure of hydrogen ion (H^+) activity in a soil solution and indicates acidity or alkalinity of the soil. The soil pH scale ranges from 0 to 14, where a pH value of 7 is neutral, pH values above 7 are basic or alkaline, and pH values below 7 are acidic. Soil pH influences many physical, chemical, and biological processes in soil that control plant nutrient availability, **cation exchange capacity** (CEC), **element toxicity**, and agronomic yields.

Availability of most macronutrients (nitrogen, potassium, calcium, magnesium, and sulfur) is optimal within a pH range of 6 to 7 and decreases outside this range. Typically, low soil pH (acidity) can lead to significant yield reductions due to nutrient deficiencies in crops. Soil acidity, particularly at pH levels below 5.5, increases solubility of aluminum and manganese in soils (Figure 2-7), causing toxicity to roots and thereby interfering with root growth and plant development (Figure 2-8). Cereal and grass crops are more tolerant to soil acidity compared to legume crops. However, significant yield reductions in wheat and barley occur at pH values below 5.2. For instance, a study in the Midwest showed that aluminum toxicity reduced wheat grain yield by 2.8% for every 1% increase in aluminum saturation (Schroder et al. 2011). Low soil pH also negatively impacts soil microbial communities (particularly bacteria), earthworm populations, rate of SOM decomposition, and efficacy of pesticides, but favors fungal pathogens and certain weed species. Bacterial (*Pseudomonas fluorescens*) inhibition of take-all disease (caused by the fungal pathogen *Gaeumannomyces graminis* var. *tritici*) in wheat reduced with increasing soil acidity due to diminished production of the antibiotic compound phenazine-1-carboxylate upon suppression of bacterial growth at low pH levels (Ownley et al. 2003).

In the inland PNW, continuous use of acid-forming N fertilizer has decreased soil pH. In particular, ammonium-based N fertilizers lower

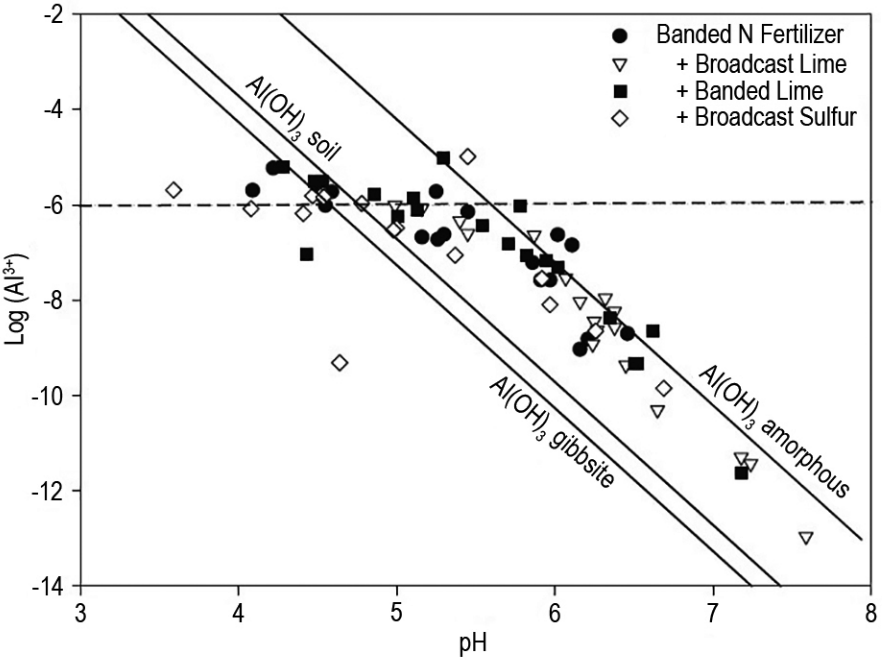

Figure 2-7. Relationship of aluminum activity and soil pH. (Reprinted from Brown et al. 2008.)

Figure 2-8. Retarded wheat root growth (right) due to aluminum toxicity. (Photo credit: CIMMYT 2016.)

soil pH because of the production of acidity (hydrogen ion) during the **nitrification** process [oxidation of ammonium-N (NH_4-N) to nitrate-N (NO_3-N)]. Most native prairie soils in the Annual AEC had neutral to near-neutral pH (6.5 to 7.2) before the onset of cultivation. Three to four decades of N fertilizer application decreased the pH in the surface foot of soil to less than 5.2 (Mahler 2002), which is at or below critical pH levels for optimum production of winter and spring cereals (pH 5.2 to 5.4), and grain legumes (pH 5.4 to 5.6) ●. In the Transition AEC, long-term (47 years) cultivation of winter wheat-spring pea (WW-SP) has considerably decreased the soil pH within the top 2 feet compared to undisturbed grassland pasture. The differences were much pronounced in the top 8-inch soil depth profile (Figure 2-9) ▲. Repeated banding of N fertilizer and limited soil mixing under reduced tillage systems, such as disk tillage and no-till, can further enhance soil acidification, particularly near the soil surface (Figure 2-9) ▲.

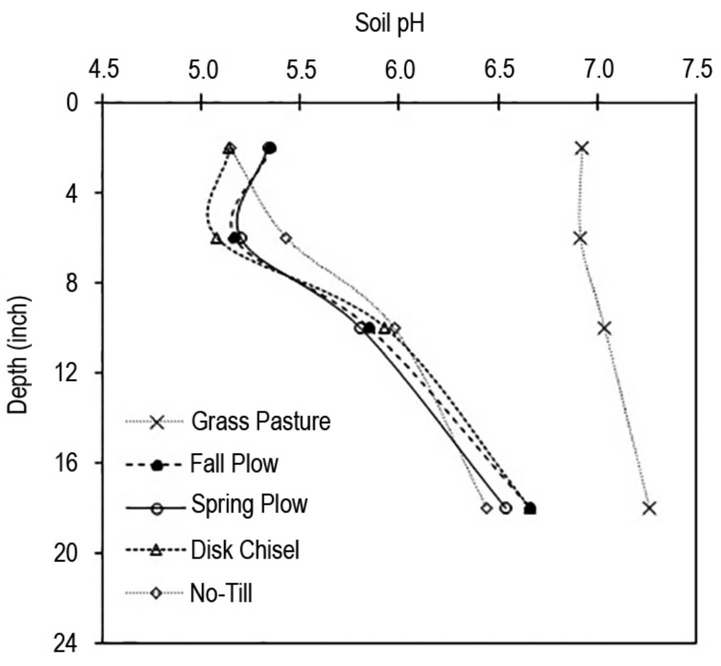

Figure 2-9. Soil profile pH under undisturbed grass pasture and four tillage systems in a long-term winter wheat-spring pea (WW-SP) rotation experiment near Pendleton, Oregon. (Awale et al. unpublished data.) ▲

Application of lime can ameliorate soil acidity (increase pH) and increase soil biological activities and crop yields. Generally, microbial activities tend to decrease with decreasing soil pH due to reduced bioavailability of organic substrates. Acidity suppresses soil enzyme activities by destroying ion and hydrogen bonds in active sites of enzymes and by altering the shape of enzymes. Increased pH caused by lime application enhances the deprotonation of organic substances and decreases bonding between organic compounds and soil particles making organic substances more accessible to microorganisms and soil enzymes. In the Annual AEC, lime application increased soil pH and maintained greater microbial biomass, soil respiration, and acid phosphatase activity; and as a result, improved wheat yield by 3 bushels per acre over non-limed plots (Table 2-7) ●. Another study in the Annual AEC revealed that liming increased soil pH above 5.5, promoted **nitrifier** populations, and increased N availability in soils from enhanced SOM **mineralization** and nitrification (Fuentes et al. 2006) ●. Mixing of a soil profile comprised of a petrocalcic (calcium carbonate) horizon under conventional tillage increased soil pH and, thereby, dehydrogenase enzyme activity over no-till in the Annual AEC due to the suppressive effects of low pH on bacterial growth (Kennedy and Schillinger 2006) ●.

Other alternatives to increase or maintain soil pH include retention of crop residues and application of organic amendments such as manure, compost, and alkaline biochar. Harvesting crop residues removes basic cations (positively charged ions) such as calcium, magnesium, and potassium, which help neutralize soil acidity. Organic materials add negative charges in soils upon their decomposition, and these negative charges can buffer acidity (Brown et al. 2008) ●. Figure 2-10 shows that application of alkaline biochar (pH 10) increased soil pH and wheat yield ▲.

Soil acidification may also be mitigated by using optimum crop N rates, nitrate-based N fertilizers, and including legume crops in cropping systems. Legumes have a natural ability to fix atmospheric N and make it available to plants, thereby reducing synthetic fertilizer N inputs. In the Transition AEC, WW-SP rotation increased soil pH compared to WW-F because of less synthetic N input requirements under a legume-based cropping system (Table 2-8) ▲.

Table 2-7. Soil surface (0–12 inch) pH and microbial parameters between non-limed and lime-applied (1.2 ton/ac) plots measured after two years following lime application under spring barley-winter wheat-spring pea (SP-WW-SP) at two sites in the inland PNW. ●

Soil parameters	Pullman, WA		Genesee, ID	
	No lime	Lime	No lime	Lime
pH	5.19	5.99	5.51	6.36
Microbial biomass carbon (ppm-C)	326	433	289	381
Respiration (ppm-C)	58	60	46.6	71.7
Dehydrogenase (ppm TPF/hr)	6.4	6.1	13.1	15.1
Acid phosphatase (ppm PNP/hr)	211	277	138	145

Adapted from Bezdicek et al. 2003.

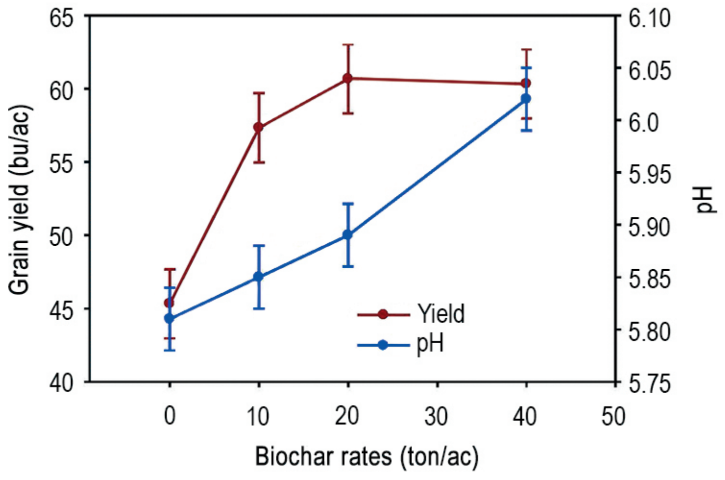

Figure 2-10. Biochar effects on soil pH and winter wheat yield in Athena, Oregon. (Adapted from Machado et al. unpublished.) ▲

Table 2-8. Soil pH measured within a 0 to 8-inch soil profile winter wheat-fallow (WW-F) and winter wheat-spring pea (WW-SP) cropping systems under conventional tillage near Pendleton, Oregon. ▲

Crop rotation	Soil pH	
	0 to 4 inch	4 to 8 inch
WW-F	5.26	5.00
WW-SP	5.35	5.17

Adapted from Awale et al. and Ghimire et al. 2017.

Cation Exchange Capacity

In soils, negative charges develop in clay minerals (permanent charge) and organic matter (pH-dependent charge). The negatively charged soil particles attract and hold positively charged ions or cations such as calcium (Ca^{2+}), magnesium (Mg^{2+}), potassium (K^{+}), aluminum (Al^{3+}), hydrogen (H^{+}), zinc (Zn^{2+}), and other molecules much like the opposite poles of a magnet attract each other. The molecules can be nutrients, water, herbicides, and other soil amendments. The adsorbed cations on the clay and organic matter particles are exchangeable with other cations in the soil solution. The sum of exchangeable cations that a soil can hold at a specific pH (or its total negative charge) is the soil's cation exchange capacity (CEC). Table 2-9 lists typical CEC values in some soil types found within the inland PNW.

The CEC of a soil affects soil fertility and plant growth. Calcium, magnesium, potassium, ammonium, and zinc are some important nutrient cations vital for plant growth. Soils with a higher CEC retain nutrient cations and maintain them in soil solution. Conversely, the nutrient cations are susceptible to **leaching** in soils with a low CEC, and as a result, plants are most likely to develop nutrient deficiencies in these soils. To this end, large quantities of fertilizers applied in a single fall application to sandy soils with a low CEC could result in loss of nutrients via leaching below the root zone. In low CEC soils, spring application of nutrient fertilizers during active plant growth stages and in split doses will improve production efficiencies. When applying nutrients to clay soils, it is best to incorporate them to prevent runoff losses.

The CEC can be occupied by either acidic (Al^{3+}, H^{+}) or basic (Ca^{2+}, Mg^{2+}, Na^{+}, K^{+}) cations. Base saturation is the percentage of the total CEC

Table 2-9. Cation exchange capacity (CEC) values and other related soil properties in soils within the inland PNW.

Soil series	CEC	EC	OM	pH	Clay
	meq/100g	dS/m	%		%
Ritzville silt loam	10.2	0.30	0.93	8.29	6.4
Palouse silt loam	18.1	0.22	2.43	6.05	22.4
Larkin silt loam	20.9	0.41	4.42	5.93	19.4
Thatuna silt loam	17.0	0.79	2.54	6.15	18.4
Woodburn silt loam	17.1	0.63	2.95	5.17	28.4
Walla Walla silt loam	16.3	0.33	2.30	6.02	15.4
Puget silt loam	11.4	0.60	2.76	6.14	22.4
Shano silt loam (SSL1)	14.9	3.06	1.13	6.27	16.4
Shano silt loam (SSL2)	10.3	1.01	1.14	5.63	13.4
Quincy fine loamy sand	6.4	0.98	0.85	8.53	7.4

Note: EC = electrical conductivity; OM = organic matter.
Adapted from Ownley et al. 2003.

occupied by basic cations. The higher the base saturation, the higher the soil pH because the basic cations help neutralize acidity. Soil's CEC influences soil's buffering capacity (resistance to rapid pH change) and, therefore, liming requirements. For instance, the lower the CEC of a soil, the faster the soil pH will decrease with time and vice versa. Therefore, low CEC soils generally require frequent liming but at lower rates of application than high CEC soils. In high CEC soils, higher liming rates are needed to reach an optimum pH.

The amounts of a particular basic cation in the CEC is crucial for soil aggregation, water flow, and **water holding capacity**. Generally, high calcium and magnesium and low sodium contents are desirable because Ca^{2+} and Mg^{2+} ions promote soil **flocculation** whereas Na^{+} ions promote soil **dispersion**. Flocculation is important because water moves mainly through large pores between aggregates, and plant roots grow between aggregates (Figure 2-2). Soil dispersion leads to restricted water infiltration and movement through soil by plugging soil pores (Figure 2-2).

Often, soil's CEC is used to determine weed and disease management in wheat production. For example, herbicide application rates may need to be adjusted with regard to soil's CEC. Generally, higher CEC soils require higher rates than low CEC soils because of greater binding ability of soils to the products, rendering them ineffective. In the inland PNW, the biocontrol activity of *Pseudomonas fluorescens* on take-all disease in wheat declined with an increase in soil CEC because high CEC bound and inactivated the antibiotic compound phenazine-1-carboxylate produced by bacteria, or adsorbed nutrients needed by the bacteria to affect biocontrol (Ownley et al. 2003).

Soil CEC is primarily influenced by soil pH, clay type and content, and organic matter content. As pH increases, the number of negative charges in soil increases, thereby increasing CEC. Therefore, adding lime and raising the pH can improve the CEC of soil. Soil CEC increases with clay and organic matter content, and decreases with sand content. Therefore, sandy soils rely heavily on the CEC of organic matter for the retention of nutrients and water. The addition of organic matter will increase the CEC of a soil; however, it requires many years to take effect (Figure 2-11) ▲.

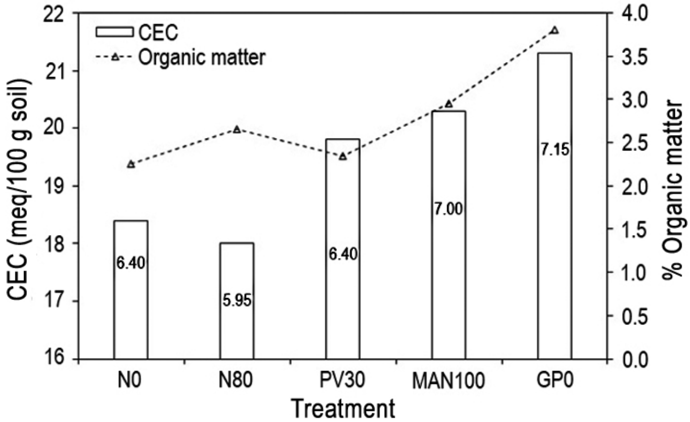

Figure 2-11. Cation exchange capacity (CEC), organic matter, and pH (number within bar) of soils under winter wheat-fallow (WW-F) in long-term (~70 yr) crop residue management experiment and grass pasture near Pendleton, Oregon. Numbers ending in the treatments denote amount of N (lb/ac) applied through inorganic N fertilizer (N), pea vines (PV), beef manure (MAN), and grass pasture (GP). (Adapted from Bandick and Dick 1999.) ▲

Soil Electrical Conductivity

In soils, cations (Ca^{2+}, Mg^{2+}, NH^{4+}, Na^{+}, K^{+}) and anions (Cl^{-}, HCO_3^{-}, $SO4_2^{-}$, NO_3^{-}) from salts dissolved in soil water carry electrical charges and conduct electricity. Soil **electrical conductivity** (EC) is a measure of the ability of soil solution to conduct electric current. The EC increases with ion (salt) concentrations in soil. The higher the concentration of ions in soil, the greater the EC measures and vice versa.

Electrical conductivity has been used to indicate total salt level in soil (salinity), although it does not indicate which salts might be present. In general, most soils contain some levels of salt that are essential for soil structure and plant growth, but excess levels can reduce crop yields by affecting soil-water balance, soil aggregation, soil microorganisms, and by inducing nutrient toxicity. Excess salts increase osmotic potential in the root zone and reduce roots' ability to extract soil water, leading to drought stress.

In non-saline soils, soil EC levels can serve as an indirect indicator of other soil properties, such as soil water content, clay content, organic matter level, soil depth, CEC, and nutrient content (nitrate-N, potassium) (Table 2-9). The conduction of electricity in soils takes place through the moisture-filled pores that occur between individual soil particles, and soil EC increases with the amount of moisture held by soil particles. To this end, EC correlates strongly with soil clay and organic matter contents due to their direct relationships with water-holding capacity as well as with soil CEC. Accordingly, use of soil EC maps has been recently increased in precision farming for delineating soil properties correlated with crop productivity. (For more information on soil EC mapping usage, see Chapter 8: Precision Agriculture.)

In soils, salts primarily develop from the weathering of parent material. However, application of fertilizers, pesticides, and other organic and inorganic amendments can add salts in soils, thereby increasing soil EC. Most microorganisms are sensitive to salt (high EC); and therefore, microbial processes such as soil respiration and nitrification decline as EC increases. Actinomycetes and fungi tend to be less sensitive than bacteria, except for salt-tolerant bacteria.

Soil Organic Matter

Soil organic matter (SOM) comprises organic materials in various states of decomposition, such as tissues of living soil organisms, plant and animal residues, and excretions from plant roots and soil microbes. SOM is a key indicator of soil health due to its influences on soil structure, aggregate stability, water storage and availability, water infiltration, nutrient storage and availability, soil biological activity, CEC, EC, adsorption of metals and agrochemicals, and pH buffering and amelioration. To this end, improvements in such soil physical, chemical, and biological properties with SOM usually correspond to greater agronomic yields (Figure 2-12) ▲. In addition, sequestering soil organic carbon (SOC) (58% of SOM) also reduces loss of CO_2, a greenhouse gas, to the atmosphere. Soil organic carbon comes from atmospheric CO_2 that is captured by plants through the process of photosynthesis.

Generally, SOM can be divided into three pools, as determined from their turnover time: active or labile (weeks to years), intermediate (years to decades), and passive or stable (hundreds to thousands of years) (Xiao 2015). The active SOM pool comprises recent plant residues in the early

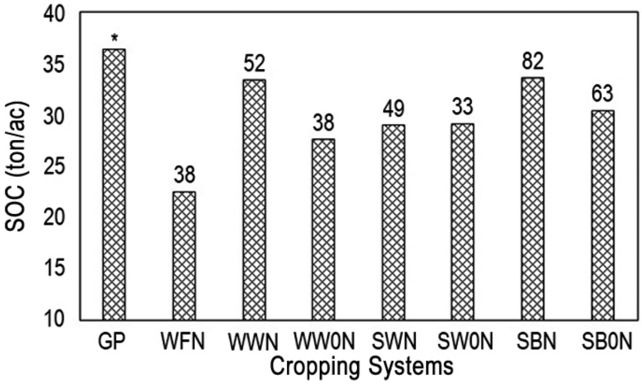

Figure 2-12. Effect of cropping systems (13 to 73 years) on soil organic carbon (SOC; ton/ac) at surface 16 inches of soil and grain yields of cereals under conventional tillage systems (except GP, no-till) near Pendleton, Oregon. Numbers above bars denote 6-year mean grain yields (bu/ac) for winter wheat-fallow (WFN); continuous winter wheat (WWN); continuous spring wheat (SWN); and continuous spring barley (SB) systems. GP represents undisturbed grass pasture. In each treatment, N at the end denotes N applied at 80 to 90 lb/ac, while 0N denotes not fertilized. (Adapted from Machado et al. 2006.) ▲

stages of decomposition and soil organisms. It serves as a food source for the living soil biological community and is responsible for nutrient release. The intermediate or slow SOM pool includes decomposed residues and microbial products that are stabilized through physical and biochemical processes. The slow pool influences soil's physical condition and nutrient buffering capacity. The stable SOM pool is highly recalcitrant (resistant to decomposition) and is important for soil aggregation and soil CEC.

Soil organic matter decomposes over the years and needs to be replaced by fresh biomass for its maintenance. Changes in SOM arise from the imbalance between inputs (from crop residues, manure, and any other organic sources) and outputs (from decay, leaching, and erosion) (Figure 2-13). Soil and crop management practices that increase SOM inputs and optimize the rate of SOM decay play an integral role in the sustainability of cropping systems. Conversely, reduced input of SOM or its rapid decomposition depletes SOM stocks. For instance, conventional tillage incorporates crop residues into soil and facilitates rapid decay of SOM by microbes due to the introduction of oxygen and greater soil residue contact (Table 2-10) ▲. On the other hand, no-till leaves most crop residues on the soil surface and favors the accumulation of SOM ▲.

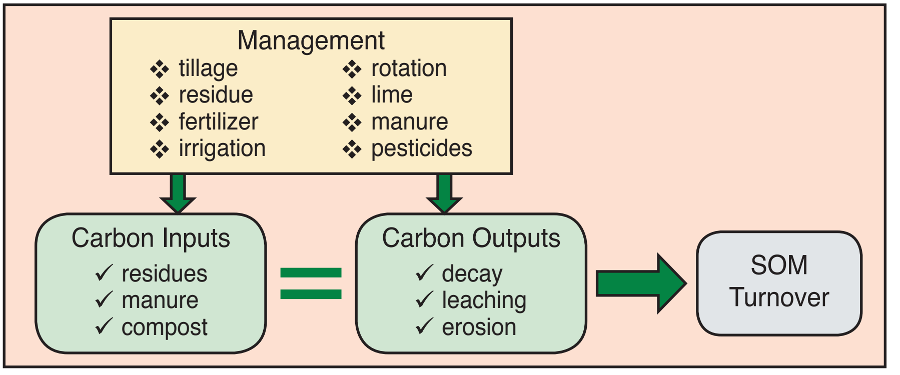

Figure 2-13. Management influences soil carbon input-output equilibrium to affect soil organic matter (SOM) dynamics.

Table 2-10. Tillage effects on soil organic carbon (SOC) dynamics at surface 2 feet in a long-term winter wheat-spring pea (WW-SP) rotation near Pendleton, Oregon. ▲

Tillage	SOC (ton/ac)		ΔSOC
	1995	2005	%
Disk/Chisel	29.2	29.7	1.5
Fall plow	29.3	30.4	3.4
Spring plow	29.3	29.5	0.3
No-till	28.7	32.7	12.0

Adapted from Machado 2011.

SOM dynamics in the inland PNW

In the inland PNW, most native soils in areas where annual precipitation exceeds 9 inches contain about 1.5 to 2.5% SOM compared to about <1% SOM in the drier regions. Conversion of native ecosystems to agriculture has tremendously depleted SOM in the inland PNW. For instance, in the Transition AEC, soil organic carbon (SOC) depleted at the rate of 196 to 428 lb/ac/yr from Walla Walla silt loam soil managed under a long-term conventional WW-F system (Machado 2011) ▲. Consequently, SOC and N stocks have depleted by up to 63% and 26%, respectively, in eight decades (Figure 2-14) ▲. In the Annual AEC, SOC (surface 4 inches) loss of 55% to 60% with a WW-SW-SP rotation was continuous under conventional tillage for more than 100 years compared to undisturbed natural prairie (Fuentes et al. 2004) ●.

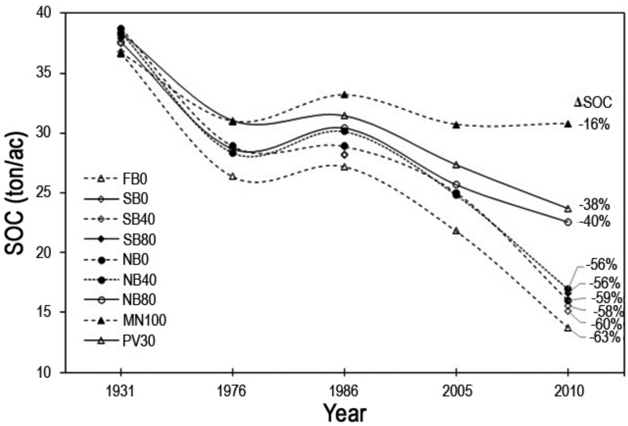

Figure 2-14. Trends in soil organic carbon (SOC) at top 24-inch depth in a long-term crop residue and nitrogen management experiment under conventional tillage winter wheat-fallow (WW-F) system near Pendleton, Oregon. Numbers ending in the treatments denote amount N (lb/ac) applied for fall residue burn (FB); spring residue burn (SB); no burn (NB); manure (MN); and pea vine (PV). Percentages of SOC change (ΔSOC) from 1931 are shown for the year 2010. (Adapted from Machado 2011 and Ghimire et al. 2015.) ▲

The loss of SOM content in the inland PNW is mainly attributed to the following factors:

1. Low quality and quantity of crop residue inputs from the predominant crop-fallow rotation (i.e., WW-F), leaving the soil bare for 14 months between crops.
2. Crop residue removal for biofuel production and for other agricultural practices, such as bedding for animals and mushroom cultivation.
3. Residue burning to eliminate the need for multiple tillage operations for seedbed preparation to ensure better seed germination or plant establishment, as well as weed and disease control.
4. Limited biomass production due to low precipitation (less than 16 inches) and its distribution.
5. Increased biological oxidation of SOM associated with multiple tillage operations (nearly eight or more passes).
6. Farming on steep slopes (up to 45%) with accelerated management-induced soil erosion under cropping systems with high soil disturbance.

The extent to which agricultural management influences changes in SOM depends on several factors, including initial levels of SOM before the management was implemented, duration of management imposed, duration of conservation practices adopted, the degree of system reaching steady-state (SOM saturation), soil and environmental conditions, and crop productivity. Therefore, it takes years to observe significant changes in SOM stocks. Determining SOM fractions sensitive to management practices and that predict SOM changes and future trends should allow early decisions for management changes that lead to SOM build-up and maintenance.

Indicators of SOM dynamics

Management induced changes in SOM are usually evaluated by determining SOC and N contents because SOM consists of approximately 58% carbon (C) and 5% nitrogen (N). However, changes in SOM take time to manifest and are difficult to discern early. Different pools of SOM and soil enzymatic activity are typically more sensitive and provide early signs of the effect of management changes than total SOM alone. Therefore, there is a growing interest in assessing early indicators of SOM dynamics such as particulate organic matter (POM), mineralizable carbon (Cmin) (soil respiration), microbial biomass carbon (MBC), dissolved organic carbon, permanganate oxidizable carbon, and potentially mineralizable nitrogen (PMN) for evaluating soil health changes (Table 2-11). Studies have shown that these indicators are strongly correlated with each other and with SOM (Figure 2-15).

Particulate organic matter

Particulate organic matter (POM) is an intermediate pool of organic matter, and typically makes up a large portion of the light fraction of SOM. It is composed of plant residues as well as microbial and microfaunal debris. Therefore, POM is a transitory or relatively labile fraction of SOM, often of recent origin (weeks to years). POM contributes to soil function in a number of ways including C-cycling and formation of other forms of organic matter such as microbial biomass and soluble C. POM is a food and energy source for soil microbes and other soil fauna, and involved in nutrient cycling, maintenance of soil structure, and stabilization of soil macroaggregates.

Table 2-11. Land-use management effects on soil organic carbon (SOC), particulate organic carbon (POC), microbial biomass carbon (MBC), and C mineralization (Cmin) of 0 to 8 inches of Palouse silt loam in eastern Washington. ●

†Management	SOC	POC	MBC	26-week Cmin
	ton/ac			
NP	28.4	8.7	1.8	2.8
NTR	26.1	4.6	1.5	2.3
NT28	23.6	3.6	1.0	2.2
NT4	22.3	2.8	0.8	2.0
CRP	16.5	2.8	0.9	2.2
BGNT4	13.5	2.1	0.7	2.3
CT	12.4	1.9	0.9	2.0

†Managements are native prairie (NP); no-till reestablished for 1 year following 10 years no-till and 3 years conventional tillage (NTR); conventional tillage followed by no-till for 28 years (NT28); conventional tillage followed by no-till for 4 years (NT4); conventional tillage followed by 11 years perennial grass under the Conservation Reserve Program (CRP); bluegrass seed production for 9 years followed by no-till for 4 years (BGNT4); >100 conventional tillage (CT).
Reprinted from Purakayastha et al. 2008.

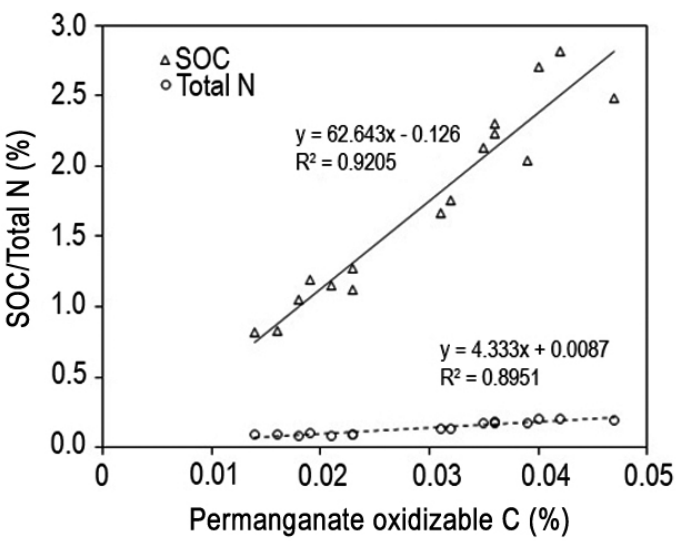

Figure 2-15. Relationship of permanganate oxidizable carbon with soil organic matter (SOM) across dryland cropping regions of the inland PNW. (Adapted from Morrow et al. 2016.)

Permanganate oxidizable carbon

Permanganate oxidizable carbon encompasses all those organic components that can be readily oxidized by potassium permanganate ($KMnO_4$), and hence, is directly related to SOC, total N, POM, **soil microbial biomass**, dissolved organic matter, and enzyme activity.

Dissolved organic matter

Dissolved organic matter is a labile pool of organic matter, present in the dissolved form in soil solution. It is comprised of leachates from plant residues and exudates from soil organisms and plant roots. It serves as energy substrate for soil microbial activity.

Soil microbial biomass and community structure

Soil microbial biomass is the active component of SOM. It is a measure of the total size of the microbial population. Table 2-12 shows typical soil microbial groups along with their relative numbers and biomass. About 80–90% of all the biogeochemical processes carried out in the soil are reactions mediated by microorganisms. Microorganisms play important roles in the decomposition of SOM, nutrient cycling and retention, formation and stability of soil aggregates, degradation of agricultural pollutants, disease suppression, and plant health improvement. Soil microorganisms respond rapidly to changes in soil environment, and microbial communities and functions are excellent indicators of soil health dynamics. Soil microbial biomass dynamics provide early warnings of soil health changes before any detectable changes occur in other soil physical and chemical properties.

Microbes act as agents for biochemical transformations of organic matter, with microbial communities acting on various components of SOM. For instance, bacteria has a low **carbon-to-nitrogen** (C:N) ratio and proliferates using easily available substrates. On the other hand, fungal biomass has a greater C:N ratio and is capable of decomposing more recalcitrant substrates, such as cellulose and lignin. Thus, fungi are typically much more efficient at assimilating and storing nutrients than bacteria. To this end, a shift toward a fungal dominance (high fungal to bacterial ratio) in the microbial community is often thought to enhance

Table 2-12. Relative number and biomass of microorganisms at surface 6-inch soil depth.

Microorganisms	Number/g of soil	Biomass (lb/ac)
Bacteria	10^8 to 10^9	350 to 4460
Actinomycetes	10^7 to 10^8	350 to 4460
Fungi	10^5 to 10^6	890 to 13380
Algae	10^4 to 10^5	10 to 450
Protozoa	10^3 to 10^4	Variable
Nematodes	10^2 to 10^3	Variable

Adapted from Hoorman and Islam 2010.

organic C accumulation and decrease its turnover rate. Accordingly, soil microbial communities differ in their responses to changes in soil management, with fungal communities usually more sensitive to these changes.

Decomposition of SOM by microbes release plant available nutrients such as N, P, and S in soil. For example, heterotrophic bacteria and fungi (requiring an energy source) convert complex forms of organic N into ammonium-N (NH_4-N), which, in turn, are converted into nitrate-N (NO_3-N) by nitrifying bacteria (*Nitrosomonas* spp. and *Nitrobacter* spp.). Certain groups of specialized bacteria such as *Rhizobioum* spp., actinomycetes, and cyanobacteria, with their symbiotic association with plant roots, can fix atmospheric nitrogen (N_2) into plant available form (NH_4). Legume-rhizobium symbiosis is the most important symbiotic relationship in nitrogen fixation. Therefore, cropping systems including legumes usually require less external fertilizer N inputs. Mycorrhizal fungi mobilize and transport nutrients (P, Cu, Zn) and water to plants by increasing the surface area of plant root systems through extensions of fungal hyphae. Microorganisms also hold nutrient elements in their biomass, which are released upon their death. Protozoa and nematodes consume other microbes to mineralize nutrients in the microbial biomass. Retention of nutrients in microbial biomass reduces nutrient losses from soils during periods of slower crop uptake.

Microbes exude sticky binding agents such as glomalin, polysaccharides, and ergosterol as they transform and ingest SOM (Figure 2-16). Fungal hyphae and bacterial filaments also favor the mechanical union of soil particles to enhance soil aggregation (Figure 2-16). Stable soil aggregates are important for soil porosity, water infiltration, and resisting erosion.

Microorganisms have many methods for controlling disease-causing organisms. Protozoa and nematodes help maintain microbial diversity in soils by consuming other soil microbes. Some bacteria and fungi generate antibiotic compounds to suppress other soil microorganisms. For instance, a bacterium *Pseudomonas fluorescens* produces a phenazine compound which inhibits take-all disease-causing fungal pathogen *Gaeumannomyces graminis* in wheat (Ownley et al. 2003). Isolates of *Chryseobacterium soldanellicola* (bacteria) exhibited significant antagonism against

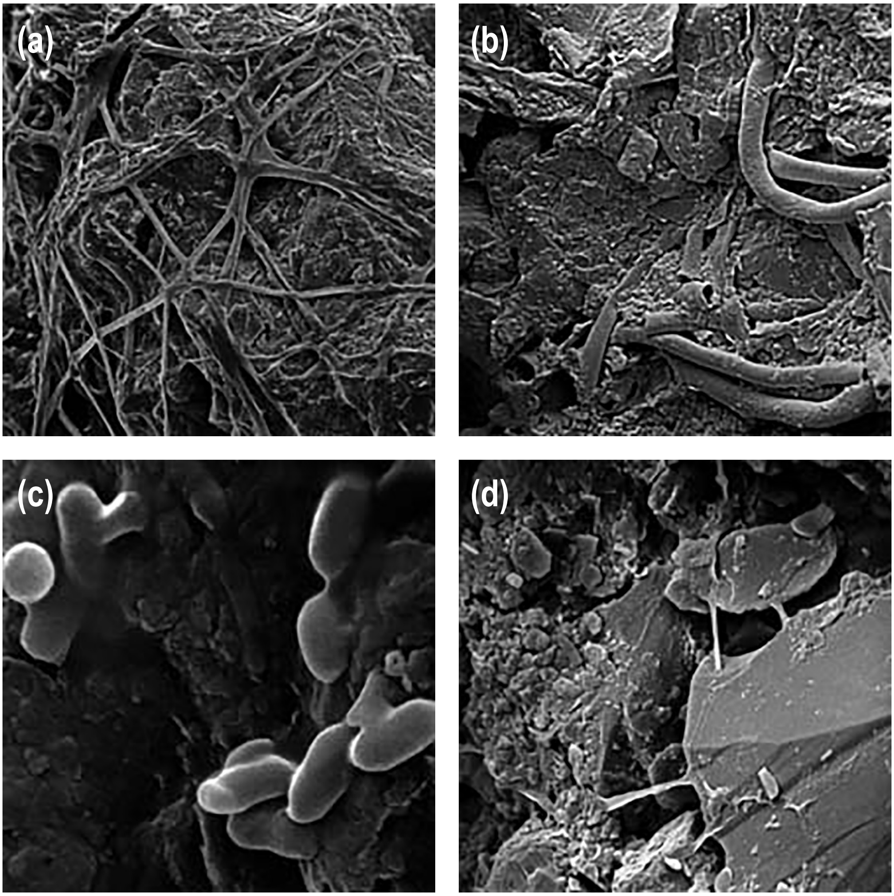

Figure 2-16. Stabilization of soil aggregates by (a) fungal mycelia (netlike), (b) fungal hyphae, (c) bacterial polysaccharides, and (d) actinomycete filaments. (Adapted from Eickhorst and Tippkoetter 2016.)

Rhizoctonia solani (a fungal pathogen that causes bare patch and root rot disease of wheat) in vitro as well as in greenhouse tests (Yin et al. 2013) ■. In addition to suppressing plant diseases, microorganisms can also stimulate plant root growth by producing biochemicals and compounds. For more information on microbial control of diseases, see Chapter 10: Disease Management for Wheat and Barley.

Soil enzymes

Soil enzymes are comprised of living and dead soil microorganisms, plant roots and residues, and animals. These enzymes play key biochemical functions in the overall process of organic matter decomposition and nutrient cycling (Table 2-13). Soil enzymes respond rapidly to changes in soil management and are potential indicators of soil health. Almost all soils contain soil enzymes but their types depend on variable substrates that serve as energy sources for microorganisms.

Soil respiration/mineralizable carbon

Soil respiration involves the oxidation of organic matter to produce CO_2 and water. It is a measure of soil biological activity and usually determined by measuring CO_2 produced by soil microorganisms and plant roots.

Table 2-13. Soil enzymes as indicators of soil health.

Soil enzyme	Role	Significance
Glucosidase	C-cycling	Energy for microbes
Galactosidase	C-cycling	Energy for microbes
Dehydrogenase	C-cycling	Energy for microbes
Invertase	C-cycling	Energy for microbes
Cellulase	C-cycling	Energy for microbes
Phenol oxidase	C-cycling	Energy for microbes
Amidase	N-cycling	Plant available N
Deaminase	N-cycling	Plant available N
Urease	N-cycling	Plant available N
Phosphatase	P-cycling	Plant available P
Arylsulfatase	S-cycling	Plant available S

Adapted from Reardon and Wuest 2016.

Mineralizable carbon refers to CO_2 produced by soil microbes during the decomposition of organic matter.

Potentially mineralizable nitrogen

Potentially mineralizable nitrogen (PMN) is a measure of mineral N released from the mineralizable organic fraction in soil. Microorganisms convert organic forms of nitrogen into plant available inorganic forms such as ammonium-N and nitrate-N (mineralization) and vice versa (**immobilization**). Whether mineral N is released or immobilized depends upon the substrate's C:N ratio. With a low C:N ratio substrate, more N, in excess of microbial requirements, is available than with a high C:N ratio substrate. PMN is an important potential source of N for crop growth and enhances microbial growth and activity. By knowing the soil's inherent ability to supply plant available N, recommended application rates of synthetic N can be determined while minimizing N losses through leaching due to over fertilization, or avoiding yield losses due to under fertilization.

Management effects on SOM indicators

Tillage and crop residue management, crop rotation and cropping intensity, and application of organic and inorganic amendments such as manure, compost, fertilizers, and lime have shown to influence fine indicators of SOM dynamics. Tillage influences soil microbial decomposition rates of SOM by influencing the availability and distribution of SOM in the soil profile, and by regulating other soil properties such as temperature, aeration, water content, and pH. Conservation tillage practices favor SOM accumulation whereas intensive tillage practices break soil aggregates and expose aggregate-protected SOM pools, increase aeration and temperature, increase soil residue contact, and promote SOM decay. Moreover, tillage-induced soil erosion can also transport SOM from eroded areas to other landscape positions (Kennedy and Schillinger 2006) ●. In the Annual AEC, SOC, particulate organic C, microbial biomass C, and 26-week mineralizable C decreased with tillage intensity and duration due to a corresponding increase in residue decomposition (Table 2-11) ●. In a similar experiment in the Annual AEC, no-till increased mineralizable C as well as permanganate oxidizable C over conventional tillage (Figure 2-17) ●. Rotating tillage practices, such as medium duration of no-till (10 years) and short interval of conventional till (3 years) followed by no-till, can lead to greater and more rapid accumulation of SOC and its fractions compared with no-till alone by distributing C accumulated during the no-till phase to deeper depths (Table 2-11) ●.

Tillage also affects soil microbial community structure by destroying fungal networks while favoring bacterial communities by increasing soil-residue contact. Such changes in soil microbial communities can consequently alter SOC storage potential. Usually, fungal dominance (higher fungus-to-bacteria ratio) in the microbial community has been linked to an increase in soil's C storage capacity due to increased carbon use efficiency, whereas bacterial dominance accelerates SOC loss via mineralization. For instance, in the Annual AEC, fungal biomarkers were greater in no-till soils whereas most bacterial biomarkers were greater in soils under conventional tillage (Table 2-14) ●. Fungal dominance under no-till was associated with a dramatic increase in SOC over conventional tillage. For more information on tillage, see Chapter 3: Conservation Tillage Systems.

Cropping systems influence both above- and below-ground residue inputs, and microbial activity. Usually, continuous cropping systems increase SOM from annual residue inputs and promote microbial biomass more than fallow cropping systems. For example, in the Transition AEC, the relative proportion of soil microbial biomass measured under annual

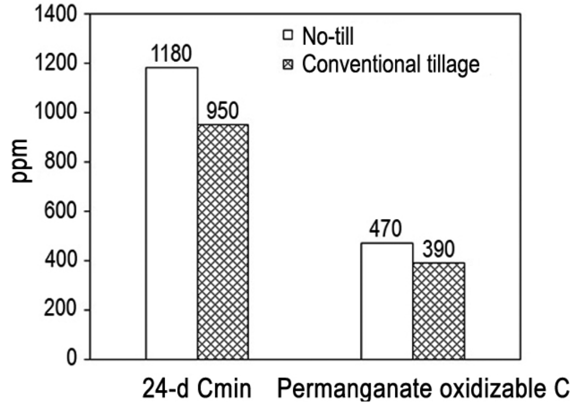

Figure 2-17. Effect of tillage on mineralizable C (24-d Cmin) and permanganate oxidizable C under winter wheat-spring barley-spring (WW-SB-SL) legume cropping system near Genesee, Idaho. (Adapted from Morrow et al. 2016.) ●

Table 2-14. Microbial community (biomarkers), determined as phospholipid fatty acid content, in surface 2-inch soils under no-till and conventional tillage in northeastern Washington.

Microbial group		Biomarkers	No-till (%)	Conventional tillage (%)
Bacteria	Gram positive	11:0 iso	0.17	0
		15:0 anteiso	2.48	2.75
		17:0 anteiso	0.75	1.06
	Gram negative	16:1 ω7c	4.62	4.50
		17:0 cyclo	0.98	1.45
		19:0 cyclo	0.27	0.84
Fungi		18:1 ω9c	6.92	6.07
		18:2 ω6c	6.44	4.38
		18:3 ω6c	1.33	0.96

Adapted from Kennedy and Schillinger 2006.

systems (WW-SP and WW-SW) and grain-fallow (WW-F) were about 50% and 25% of undisturbed grass pasture (Figure 2-18). Diversified cropping systems create a more favorable soil environment for microbial and faunal community due to increased root activity and exudates. For instance, dehydrogenase enzyme activity in a top 2-inch soil depth was higher under a SW-SB rotation than under continuous spring wheat in the Grain-Fallow AEC (Schillinger et al. 2007). Inclusion of cover crops in a cropping sequence, particularly legumes, can increase soil available N along with other improvements in soil properties such as aggregation, infiltration, and weed control. Table 2-15 shows that the winter wheat-winter pea (WW-WP) rotation increased SOC, total N, and mineralizable N compared with other cropping systems without legumes. For more information on cropping systems, see Chapter 5: Rotational Diversification and Intensification.

Residue composition determines its decomposition rate, and thus microbial respiration and microbial biomass and community structure. Accordingly, residue composition influences microbial release of nutrients. Microorganisms also require soil nutrients for their own growth, and the C:N ratio of residues generally determines whether nutrients are released (mineralized) and available for plant uptake or

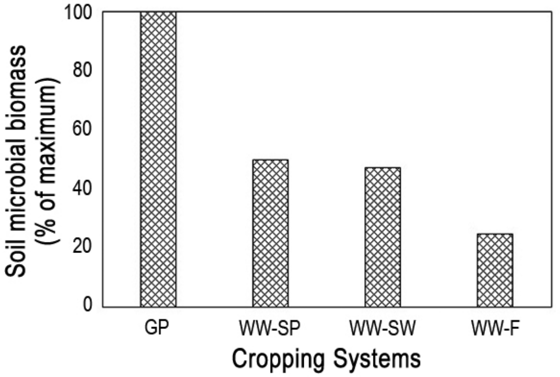

Figure 2-18. Soil microbial biomass in long-term cropping systems (winter wheat-spring pea, WW-SP; winter wheat-spring wheat, WW-SW; and winter wheat-fallow, WW-F) in relation to grass pasture (GP) near Pendleton, Oregon. (Adapted from Collins et al. 1992.) ▲

Table 2-15. Effect of tillage and cropping systems on soil organic carbon (SOC), soil total nitrogen (N), and potentially mineralizable nitrogen (PMN) near Moro, Oregon. ■

†Management	SOC	Total N	PMN
	%		ppm
NT WW-WP	1.268	0.095	73.9
NT WW-ChF	1.147	0.085	41.1
NT WW-SB-F	1.125	0.093	43.5
CT WW-F	1.053	0.081	41.6

†Managements are no-till winter wheat-winter pea (NT WW-WP), no-till winter wheat-chemical fallow (NT WW-ChF), no-till winter wheat-spring barley-fallow (NT WW-SB-F), and conventional tillage winter wheat-fallow (CT WW-F).
Reprinted from Morrow et al. 2016.

assimilated (immobilized) in the microbial biomass. Therefore, the availability of essential nutrients such as N and P can, in turn, influence soil microbial biomass. Table 2-16 shows N mineralization under wheat-based cropped and undisturbed native soils, with and without wheat straw addition, from five different precipitation zones in northeastern Oregon. In general, soil N mineralization increased with precipitation, undisturbed native soils had higher mineralized N than cropped soils, and wheat straw addition reduced mineralized N (or immobilized) than when no residue was added (Table 2-14). For further information on residue characteristics, see Chapter 4: Crop Residue Management.

Table 2-16. Effect of wheat straw addition on soil nitrogen (N) mineralized from 0 to 8-inch depth of cropped (wheat-based) and native soils across different precipitation zones in northeastern Oregon.

Soil	Precipitation inch	†Soil N mineralized (ppm)		
		No residue added	3 ton/ac residue	6 ton/ac residue
Cropped				
Cowsly	>20	57	26	41
Athena	16 to 20	61	42	48
Walla Walla	14 to 16	41	13	26
Ritzville	10 to 14	29	5	14
Adkins	<10	28	8	23
Native				
Cowsly	>20	114	72	89
Athena	16 to 20	123	60	79
Walla Walla	14 to 16	109	77	70
Ritzville	10 to 14	NA	NA	NA
Adkins	<10	29	−3	−1

†Negative values indicate net immobilization; NA = not available.
Adapted from Douglas et al. 1998.

Addition of organic materials from external sources such as manure, biosolids, and compost represent direct input of organic C as well as other important plant nutrients (e.g. N, P). Similarly, balanced nutrient fertilization and effective management of weeds, **pests**, and diseases would likely increase crop biomass and the amount of residue returned to the soil. Application of lime increases soil pH that creates favorable conditions for soil biological activity. Studies have also shown a strong and positive correlation between additions of organic and inorganic amendments with soil biological activity which, in turn, is responsible for improving soil physical and chemical properties (Tables 2-3 and 2-7). In the Transition AEC, application of organic manure and pea vines increased β-glucosidase, arylsulfatase, and urease activities compared to inorganic N application in a WW-F system (Figure 2-19) ▲. See Chapter 7: Soil Amendments for more information on soil organic and inorganic amendments. See Chapter 9: Integrated Weed Management, Chapter 10: Disease Management for Wheat and Barley, and Chapter 11: Insect

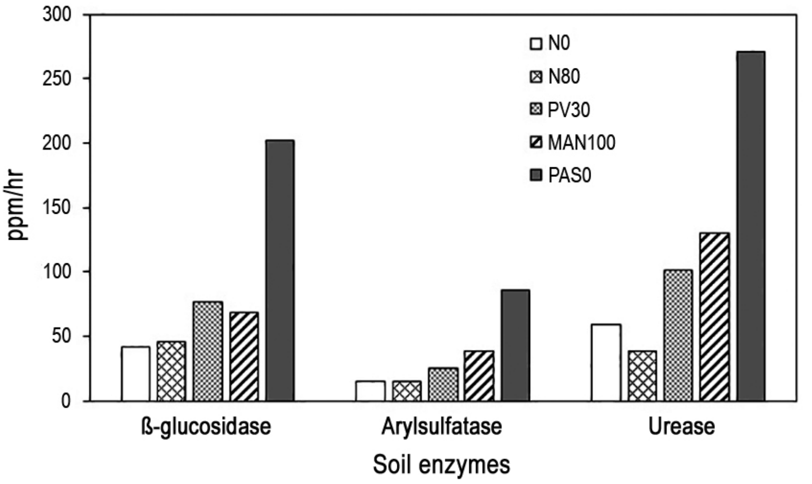

Figure 2-19. Management effects on enzyme activities of soils under winter wheat-fallow (WW-F) in a long-term crop residue management experiment and grass pasture near Pendleton, Oregon. Numbers ending in the treatments denote amount of nitrogen (lb/ac) applied through inorganic nitrogen fertilizer (N), pea vines (PV), beef manure (MAN), and grass pasture (PAS). (Adapted from Bandick and Dick 1999.) ▲

Management Strategies for more information on management of soil fertility, weeds, insects, and pests.

Soil Fauna: Earthworms, Nematodes, and Soil Insects

Soil fauna, including earthworms, nematodes, and insects, are essential in soil structural development; water, air, and nutrient cycling; SOM turnover; suppressing harmful pests; and enhancing beneficial microorganisms in the soil profile. For instance, the burrowing activity of nematodes creates a network of surface-connected tunnels which increase air permeability and water infiltration rates. In addition, burrowing activity also promotes soil mixing and increases soil and plant residue contact that favors organic matter decomposition and nutrient release. The feeding and casting activity of earthworms improve aggregate stability and enhance microbial activity (Figure 2-20).

Soil faunal measurement techniques involve counting the size of their populations. Management practices, such as tillage, residue cover, crop rotation, and liming, that alter soil microenvironments and disturb their

Figure 2-20. Worm excrement (cast) increases soil microbial activity and soil aggregate stabilization. (Photo by Wikimedia Commons.)

habitats and food sources influence the populations of soil fauna. In the Annual AEC, increase in earthworm populations is usually associated with no-till relative to conventional tillage due to lower disturbance, less physical injury, and more food supply (Figure 2-21) ●. Soil fauna is usually concentrated at locations with higher organic matter content because SOM not only serves as a food source to soil fauna but it also retains soil moisture that is necessary for soil faunal survival and reproduction. In the Annual AEC, higher SOM under no-till promoted greater earthworm densities, but the densities remained low under conventional tillage with low SOM content (Umiker et al. 2009) ●. For more information on soil fauna, see Chapter 11: Insect Management Strategies.

Soil Health Assessment

A healthy soil is the foundation of sustainable agricultural production. The concept of soil health is gaining importance due to increasing pressure to sustainably produce food, feed, fiber, and fuel for the world's increasing population. Compared to air and water quality assessments that are well defined, soil health assessments are more difficult in that conditions

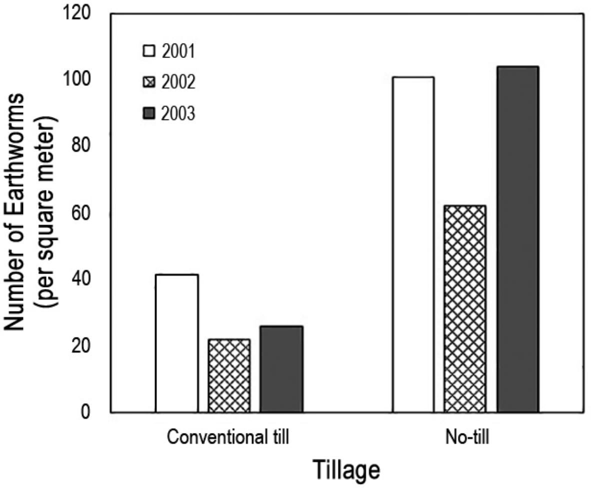

Figure 2-21. Effect of tillage on mean earthworm density under winter wheat-spring barley-spring pea (WW-SB-SP) rotation in northern Idaho. (Adapted from Johnson-Maynard et al. 2007.)

considered healthy for one soil type and crop in a particular environment may not be the same for another soil type and another crop in a different environment. Agricultural landscapes exhibit a high degree of spatial variability and different crops require different conditions. In addition, the slow nature of soil degradation seldom leads to immediate cropping system failures, and therefore subtle deleterious effects of a particular soil management regime on soil health and function are often overlooked by growers until the problem is much worse. The major challenge of soil health research and assessment programs is the lack of a standard set of soil indicators that are sensitive to changes in management and are cheap and accessible. It would be difficult to establish a single health indicator that could effectively judge all soil changes in response to management; hence, comprehensive standards for assessing soil health are needed. In response, the concept of a minimum data set of indicator groups of soil function required for soil health assessment has emerged (Table 2-1; Figure 2-22). However, the components of a minimum data set are not universal because of inherent soil variability. Therefore, any set of indicators may not provide a one-size-fits-all approach to soil health assessment across all soils and all environments. Recently, Morrow et al. (2016) proposed a set of seven criteria that establish a specific framework to judge the effectiveness of soil health indicators for soil health assessments across agroecosystems in the inland PNW:

1. Evidence based: The indicators capture measurable soil properties and processes, supported by scientific research and experimentation.
2. Sensitive to change: The indicators respond to management practices and are applicable across a range of soils and soil conditions.
3. Logistically feasible: The indicators are feasible within time constraints of effective decision making.
4. Accurate and precise: Indicators provide repeatable results with low variability, determined using standardized methods.
5. Cost effective: The cost of implementation is reasonable and within the economic constraints of the land management system.
6. In situ or undisturbed samples: Tests can be performed in situ or on relatively undisturbed samples to capture real field conditions.
7. Valued: The information is useful and interpretable for sound management decisions.

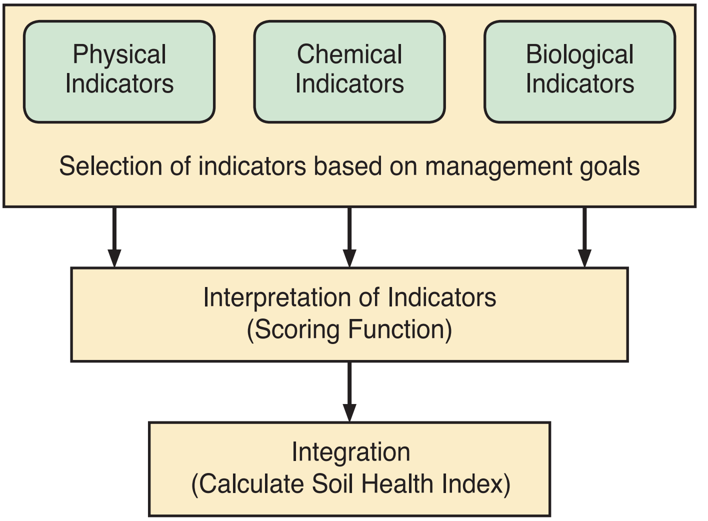

Figure 2-22. Conceptual framework of soil management assessment framework. (Adapted from Andrews et al. 2004.)

Soil Health Assessment Indices

Advances have been made in managing soils by integrating physical, chemical, and biological properties and processes in order to promote long-term soil sustainability. To this end, several indices and tools have been developed to provide a systematic framework for assessing soil health. Examples of such assessment tools include the Cornell assessment of soil health (Moebius-Clune et al. 2016), Haney's soil health test (Haney 2014), the soil management assessment framework (Andrews et al. 2004), and the USDA Natural Resources Conservation Service soil quality test kit (USDA 2001). Soil health assessments are performed by comparing a site against an adjacent, undisturbed site with the same soil type, whenever possible. Under situations where reference sites are not accessible, tracking temporal changes in appropriate indicators can detect management influences on soil health. Accordingly, soil assessment tools are usually framed up with three steps: (1) identification of indicators based on management goals, (2) indicator interpretation or scoring function (e.g., 0 to 10 or low to high, with an indicator score of 10 or high representing the highest potential function for that system), and (3) integration of all indicator scores into a single overall soil health score (Figure 2-22).

Applicability of Soil Health Indices in the Inland PNW

The Haney's soil health testing method is based on soil microbial activity, as determined from the measurement of CO_2 during the first day after rewetting a dried, ground soil sample. The test predicts a soil health score (1 to 50; the higher the better) as well as an estimate of N fertilizer credits from determinations of microbial activity and water soluble organic C and N. However, the reliability of the Haney's test as an indicator of soil health has been questioned because of the difficulty in getting reproducible test results (high random variability associated with test methodology) (Sullivan and Granatstein 2015). Recently, Washington State University researchers (Morrow et al. 2016) reported on their research evaluating the Haney's test using soils under diverse cropping systems and tillage intensities across the inland PNW. It was revealed that 1-day microbial activity (mineralizable C) was highly variable (coefficient of variation from 3% to 50%) such that the water soluble C and N did not correlate with 1-day mineralizable C but correlated with mineralizable C from longer (24-day) incubation time. The results are in sharp contrast from the assumption made in Haney's testing method that 1-day mineralizable C correlates well with water soluble C and N. Overall, the Haney's soil health index was not highly sensitive to tillage and cropping practices in the inland PNW. Therefore, Haney's soil health scoring method would necessitate further validation through extensive field research and calibration prior to its usage in the inland PNW.

Unlike Haney's test, the Cornell soil health assessment, the soil management assessment framework, and the USDA-NRCS soil quality test kit focus on several other physical and chemical properties of soils along with labile SOM pools and biological activity. Accordingly, these soil health assessment methods have been widely used across diverse soils and management practices with effective outcomes (Cherubin et al. 2016; Idowu et al. 2008; Karlen et al. 2008; Seybold et al. 2002; Wienhold et al. 2008). Usage of such indices to assess soil health in the inland PNW has been scarce. However, the indices could potentially be used to manage soil health under dryland farming systems within the inland PNW. For instance, following the approach of the soil management assessment framework, a comprehensive evaluation of soil health assessments across tillage (no-till vs. conventional tillage) and cropping systems (continuous small grains, including wheat, pea, and lentils vs. wheat-fallow) in the inland PNW was conducted (Figure 2-23). The researchers used data sets from Natural Resources Inventory monitoring sites located in Major Land Resource Area 9 (comprising the Palouse and Nez Perce Prairies, southeastern Washington, northwestern Idaho, and northeastern Oregon). Overall, the outcome of the assessment was that a continuous cropping system generally had soil health improvements (higher index values) over a wheat-fallow system (lower index values), with significant benefits observed when coupled with a no-till system (Figure 2-23).

Similarly, a quantitative soil health index was developed to evaluate soil health in fields with three different management systems (organic, conventional or non-organic, and integration of both) under apple orchard production in Washington (Table 2-17). Soil health indicators (physical, chemical, and biological) were scored based upon their effects on four soil functions (water entry, water movement and availability, resistance to

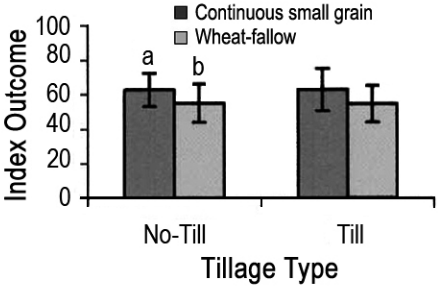

Figure 2-23. Soil management assessment framework index outcomes for cropping system and tillage management across the inland PNW. Treatments or land uses labeled with different letters are significantly different at α = 0.05. Error bars represent one standard deviation from the mean. (Reprinted from Andrews et al. 2004.)

Table 2-17. Soil quality rating based on four soil functions for conventional or non-organic, integrated, and organic systems of apple production in Washington.

Treatment	Conventional (non-organic)	Integrated	Organic
Water entry	0.153	0.235	0.213
Water movement and availability	0.208	0.235	0.205
Resist degradation	0.185	0.145	0.225
Sustain productivity	0.255	0.213	0.238
Total soil quality index	0.783	0.923	0.878

Reprinted from Glover et al. 2000.

surface structure degradation, and sustainable production). The total soil quality index for each management was obtained by summing all scores. Overall, the study concluded that the integrated system had soil health advantages over the other two systems and that increasing organic matter and reducing tillage were key aspects.

Several soil health assessment guides, such as the Idaho NRCS soil health assessment card (USDA-NRCS 2014), the Palouse and Nez Perce Prairies soil quality card guides (USDA-NRCS 2004), and the Willamette Valley soil quality card guide (OSU 2009), are also available for use across the inland PNW.

Grower Considerations: Improving Soil Health in the Inland PNW

The main goal of every grower is to develop a farming enterprise that is economically and biologically sustainable. Adhering to soil health concepts to evaluate farm management should assist growers achieve this goal. Soil health assessment indices should be tailored to address the goals of each farming enterprise. Variations in soils, temperature, and environments in the inland PNW AECs necessitate the development of site-specific soil health indices to guide growers in improving soil health on their farms. Working very closely with Extension agents and other government agencies, growers should be able to assess the effect of management practices on soil health. Consequently, the efforts to manage soil health require continuous monitoring of soil health changes and making appropriate adjustments in management practices. Overall, in the inland PNW, soil health can be improved by the adoption of one or a combination of the following management strategies:

- Reduced or minimal soil disturbance through conservation tillage practices such as no-till, strip tillage, subsurface ridge till, and undercutter sweep (Chapter 3: Conservation Tillage Systems).
- Minimization of bare-fallow systems with alternative cropping systems such as chemical-fallow, annual cropping, and cover cropping (Chapter 5: Rotational Diversification and Intensification).
- Increased residue retention and cover (Chapter 4: Crop Residue Management).
- Elimination of crop residue burning (Chapter 4: Crop Residue Management).
- Increased cropping intensification and crop diversity (Chapter 5: Rotational Diversification and Intensification).
- Balanced and efficient fertilization approach to minimize nutrient loss, excessive weed growth, and pest competition and to maximize crop production and biomass return. Inclusion of legume cover crops in a crop rotation and organic amendments reduce N fertilizer needs and slow down soil acidification (Chapter 5: Rotational Diversification and Intensification; Chapter 6: Soil Fertility Management; Chapter 7: Soil Amendments).

- Application of organic amendments such as manure, compost, residues, etc. (Chapter 7: Soil Amendments).
- Integrated management of diseases, pests, and weeds through balanced fertilization, crop rotation, and cover crops (Chapter 5: Rotational Diversification and Intensification); minimum tillage (Chapter 3: Conservation Tillage Systems); and chemical control (Chapter 9: Integrated Weed Management; Chapter 10: Disease Management for Wheat and Barley; Chapter 11: Insect Management Strategies).
- Application of lime and alkaline biochar to ameliorate soil acidity (Chapter 6: Soil Fertility Management).

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