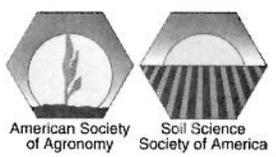


Soil Management: Building a Stable Base for Agriculture

Jerry L. Hatfield and Thomas J. Sauer, Editors

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Fallow Effects on Soil

David C. Nielsen and Francisco J. Calderón

Fallow has been defined as a farming practice wherein no crop is grown and all plant growth is controlled by cultivation or chemicals during a season when a crop might normally be grown. (Haas et al., 1974). Fallow as a practice, associated with crop rotation, had its origins in Mediterranean agriculture (Karlen et al., 1994) and continues to be used throughout the semiarid and arid regions of West Asia and North Africa (Ryan et al., 2008). Additionally, summer fallow has been practiced widely across the 15 western states of the United States and the farmed areas of the prairie provinces of Canada in response to widely varying precipitation from year to year. For example, precipitation in any given year for a specific site in the central Great Plains region of the United States may range from double to less than half of the long-term average (Greb et al., 1974).

The primary reason for summer fallow is to stabilize crop production by forfeiting production in one season in anticipation that there will be at least partial compensation by increased crop production the next season. Summer fallow was almost universally adopted in the semi-arid U.S. Great Plains in response to the 1930s dust bowl, higher wartime prices, and much improved tractor power systems and implements needed to control weeds during fallow (Greb, 1979). Other objectives of fallowing are to maximize soil water storage through improved water intake, snow trapping, and decreased evaporation; maximize plant nutrient availability; minimize soil erosion hazards; and minimize energy and economic inputs (Greb, 1979). Soil texture determines water holding capacity, thereby influencing how well fallow can buffer the influence of variable growing season precipitation on crop yield.

Fallow systems in semiarid regions can vary in fallow frequency (one crop in 2 yr, two crops in 3 yr, three crops in 4 yr, etc.), with the more frequently cropped systems generally producing more surface crop residues (Cantero-Martinez et al., 2006). Crop residue produced degrades over the fallow period at varying rates depending on the weed control methods used and climatic conditions. Fallow systems vary in intensity of tillage needed to control weeds during the noncrop period, and include maximum tillage (plowing and harrowing), conventional bare fallow (shallow disking and rod-weeding), stubble mulch (undercutting), minimum tillage (combinations of residual and contact herbicides with subsequent tillage), and no-tillage (use of only herbicides to control fallow weed growth). Tillage knocks down, cuts up, and incorporates standing and flat crop residue, facilitating organic matter mineralization by bringing together substrates, microbes, water, and oxygen. The various combinations of fallow frequency, tillage, and chemical weed control have effects on surface soil residue quantity, orientation, and duration, which subsequently affect surface soil organic matter content, soil physical structure, precipitation storage, nutrient availability, microorganisms,

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erosion potential, and ultimately, crop production. This chapter reviews results of some of the past research conducted to determine the effects of varying methods of fallow on these parameters.

Effects on Organic Matter

Soil organic matter (OM) is a key indicator of soil quality as it influences biological activity, serves as a nutrient reservoir, and impacts soil aggregation (Doran and Parkin, 1996; Wienhold et al., 2006; Ryan et al., 2008). Rasmussen and Collins (1991) stated that soil OM assumes a pivotal role in semiarid rainfed areas because of its disproportionate influence on water and nutrient availability and on yield stability. Cropping systems that employ fallow generally have negative impacts on soil OM due both to decreased crop residue production and due to tillage used for weed control during the fallow period (Biederbeck et al., 1984; Campbell and Souster, 1982; Campbell et al., 2000; Mikha et al., 2006; Rasmussen and Collins, 1991; Rasmussen and Parton, 1994; Peterson et al., 1998; Ryan and Pala, 2007; Williams, 2004). When sod was broken and placed into a wheat (*Triticum aestivum* L.)–fallow rotation at Sidney, Nebraska, OM declined by 20% for no-till, 25% for mulch till, and 37% for plow till in just 16 yr (Follett and Schimel, 1989). Golchin and Asgari (2008) concluded that frequent tillage and use of a summer fallow–small grain system in northeast Iran caused soil quality to deteriorate through decreased soil organic C and increased erosion as structural stability declined. However, Williams (2008) showed that the typical decline in soil organic C in a tilled winter wheat–fallow system in north-central Oregon did not occur with applications of manure containing 145 kg N ha⁻¹ per crop.

Annual cropping produces more crop residues than systems employing fallow and can gradually restore some of the organic matter lost in fallow systems. Bowman et al. (1999) and Ortega et al. (2002) reported increases in total soil organic C and N in the 0- to 5-cm depth, as fallow frequency decreased for dryland cropping systems in northeast Colorado. Similar increases in total organic C and N were reported by Campbell et al. (1999) for the 0- to 7.5-cm layer due to increased cropping

intensity after 12 yr when comparing spring wheat–fallow to continuous spring wheat in southwestern Saskatchewan. Additionally, Bowman et al. (1999) found that particulate OM-C doubled and particulate OM-N and soluble organic C increased by one-third when a cropping system moved from wheat–fallow to continuous cropping. Pikul and Aase (1995) also reported significantly greater soil organic C in the 0- to 12-cm layer in an annual spring wheat system compared with a wheat–fallow system in Montana, and attributed the difference to 40% less crop residues returned annually to the soil in the wheat–fallow system. Mikha et al. (2006) found that tillage reduction and elimination of fallow increased total soil organic C in the 0- to 7.5-cm depth at four Great Plains locations extending from Bushland, Texas to Swift Current, Saskatchewan. Wood et al. (1991) reported a similar increase in soil organic C in response to a reduction in tillage and elimination of fallow. Ryan et al. (2008) found that soil OM levels in Syria were increased when fallow in a wheat–fallow cropping system was replaced with a crop (particularly a legume) and when N fertilizer was added, presumably in response to increased amounts of biomass produced.

Reducing tillage can likewise result in higher OM levels (Havlin et al., 1990). Halvorson et al. (1997) found 9% higher total C and 19% higher total N in the 0- to 2.5-cm soil layer of a no-till wheat–fallow system in northeastern Colorado compared with a conventional till wheat–fallow system 22 yr after implementation of the two systems. In a wheat–sorghum [*Sorghum bicolor* (L.) Moench]–fallow study in the Texas Panhandle, Unger (1991) reported a nonsignificant tendency for the no-till system to have higher OM levels than the stubble mulch tillage system 6 to 8 yr after the systems were established. Doran et al. (1998) reported that fallow tillage management practices greatly influenced the content and distribution of OM in the soil, with both organic C and N declining by 35 to 40% in the 0- to 7.6-cm layer following plowing of a native sod site in western Nebraska. They attributed the changes to (i) redistribution, mixing, and dilution with depth due to tillage; (ii) biological oxidation of soil OM (Doran and Smith, 1987); (iii) reductions in C and N inputs to soil due to changes in plant inputs due to

crop and fallow management; and (iv) erosion loss from and deposition on surface soil. Losses of surface soil C and N are generally greatest during the first 8 to 10 yr after sod is cultivated, although losses continue to occur at a slower rate thereafter (Peterson and Vetter, 1971; Campbell et al., 1976). The generally moist, warm late spring and early summer periods in the central Great Plains create favorable conditions to decompose soil OM (Bowman et al., 1999), and those favorable conditions are enhanced by tillage operations (Doran et al., 1998).

Effects on Soil Physical Structure

Tillage for weed control during the fallow period is reported to have varying effects on the soil bulk density in the surface layer. The lack of a consistent response of bulk density to tillage in fallow systems may be attributable to amount of time and precipitation between tillage and sampling, type of tillage (disk vs. sweep vs. plow), depth of tillage, and soil type (Mikha et al., 2006). Results also vary with sampling depth. Generally, tillage will decrease bulk density in the tilled soil layer. However, tilled soil may eventually reconsolidate due to gravity, precipitation, and traffic. Mielke and Wilhelm (1998) found a bulk density of 1.19 Mg m^{-3} in the 0- to 7.6-cm layer of a silt loam soil in western Nebraska that had been plowed during the fallow period of a wheat-fallow system compared with a bulk density of 1.27 Mg m^{-3} for the system under no-till management. Halvorson et al. (1997) reported greater bulk densities in no-till vs. conventional till wheat-fallow after a 15-yr study comparing the two systems in northeastern Colorado. Those differences were seen at all sampling depths from 0 to 20 cm, with the greatest difference (17% higher bulk density in no-till) occurring in the 2.5- to 5.0-cm depth interval. Mielke et al. (1986) reported no difference in bulk density in the 0- to 7.5-cm layer of an Alliance silt loam (Aridic Argiustolls) in western Nebraska due to tillage in a wheat-fallow system 8 mo after the tillage occurred. On the other hand, they reported lower bulk density under no-till for a Duroc loam (Pachic Haplustolls). Mielke et al. (1984) and Unger (1991) reported no effect of tillage treatments on bulk density, while

Unger and Fulton (1990) found greater bulk density under conventional stubble mulch tillage than under no-till in the 4- to 7-cm depth. Pikul and Aase (1995) analyzed the combined effects of tillage and cropping intensity on bulk density in northeastern Montana. They found that after 9 yr of cropping, the spring wheat-fallow conventional till system had higher bulk density in the surface to 12-cm layer than in either the annual spring wheat no-till system or the annual spring wheat system with fall and spring tillage. Pikul et al. (1997) found no difference in bulk density in the 0- to 0.08-cm, 0.08- to 0.15-cm, and 0.15- to 0.30-cm surface soil layers of a Williams loam (fine-loamy, mixed Typic Agriboroll) in eastern Montana when comparing wheat-fallow no-till and conventional till systems and continuously cropped systems over a 5-yr period.

Pikul et al. (2006) reported greater water-filled pore space for systems employing fallow compared with continuously cropped systems at two northern Great Plains locations, but mixed results regarding the effects of tillage on water-filled pore space. The mixed results are likely to be a result of variations that occur with time of sampling and the large seasonal fluctuations that occur in water-filled pore space during different rotational phases. Mielke et al. (1986) found greater water-filled pore space in both the Duroc loam and Alliance silt loam mentioned above under no-till management, and lower air permeability and hydraulic conductivity under no-till.

Tillage for weed control during fallow periods can also create soil conditions that can restrict root growth and development. Results of a study conducted at Tribune, Kansas, where a sweep plow was used in a conventional till wheat-fallow system, showed increased bulk densities (compared with sod and no-till) at 30 to 40 cm (McVay et al., 2006). Many tillage operations at a consistent depth can lead to destruction of plant roots, and without plant roots to reinforce the soil, machine-induced compaction can occur (Ess et al., 1998). Pikul and Aase (1995) also identified a bulk density maximum occurring at about 10 cm in a wheat-fallow conventional tillage system, coinciding with the depth of the shallow sweep tillage operation conducted during the fallow periods.

Changes to the soil physical condition by reducing the frequency of fallow in a

cropping system may take many years. After 15 yr of no-till management in dryland wheat systems varying in fallow frequency (which can conversely be seen as cropping intensity) from wheat-fallow to continuously cropped wheat-corn (*Zea mays* L.)-millet (*Panicum miliaceum* L.), Benjamin et al. (2007) found no effects of fallow frequency on bulk density, pore size distribution, water holding capacity, or saturated hydraulic conductivity in northeastern Colorado.

No-till fallow can affect soil aggregation through decreased tillage frequency and soil disruption. Unger and Fulton (1990) reported lower mean weight diameter of water-stable aggregates and lower porosity in the 4- to 7-cm layer under conventional stubble mulch tillage than under no-till. Pikul et al. (2006) showed that mean weight diameter was greater in a continuously cropped winter wheat system at Bushland, Texas than in a wheat-sorghum-fallow system leading to improved soil structure and greater resistance to erosion. Similarly, Blair et al. (2006) reported greater mean weight diameter under continuously cropped wheat compared with wheat-fallow for two Vertisol soils in northeastern New South Wales, Australia. They suggested that the poorer structural stability as well as less cover in fallow systems could result in increased erosion risk.

Effects on Soil Water

As stated earlier, one of the primary driving factors for the implementation of cropping systems that employ fallow periods is to store water in the soil profile to mitigate the effects of widely varying precipitation amounts in semiarid environments. Studies conducted over many years and at many locations confirm the increases in stored soil water at planting that occur in systems that employ fallow compared with continuously cropped systems.

Differences in amount of water stored in the soil over the fallow period vary due to differences in precipitation storage efficiency that occur with varying methods of weed control used during the fallow period and the variability in timing and amount of fallow period precipitation. As tillage intensity decreases through the use of minimum

disturbance tillage implements such as rod-weeders and sweep plows and the use of herbicides, more crop residues remain on the soil surface for longer periods of time during the fallow period. Those increased residues are responsible for decreased runoff, decreased evaporation, and increased infiltration, resulting in greater precipitation storage efficiency (Unger, 1978).

Several studies have shown that crop residue management during fallow is important to reduce runoff and evaporation. Russel (1939) quantified the effects of winter wheat residues on runoff and soil water evaporation during the second summer of fallow in a winter wheat-fallow system in eastern Nebraska. He reported runoff decreasing from 60 to 0 mm as quantity of wheat residue on the soil surface went from 0 to 9 Mg ha⁻¹, and evaporation declining from 255 mm to 182 mm, respectively. Results from a study conducted on clay soils in southeastern Queensland, Australia, showed 22 to 35% greater runoff during the fallow period of a winter wheat-fallow system managed as bare fallow (5% soil surface cover by residue) compared with no-till management (64% surface cover) (Freebairn and Wockner, 1986). In another study from southeastern Queensland, Tullberg et al. (2001) investigated both tillage and controlled traffic effects on runoff in a dryland cropping system with periods of fallow between production of corn, sorghum, and wheat. They reported mean runoff over a 3-yr period to be 63 mm per year greater in a wheel-tracked area vs. a controlled traffic area and 38 mm per year greater under stubble mulch tillage vs. no-till. Decreased runoff in response to greater surface crop residues has been attributed to reduced soil crust formation and slowed flow rate across the surface due to greater flow path tortuosity and greater resistance to flow (Steiner, 1994).

In northern Mississippi where fallow is not a common production practice, Wilson et al. (2008) found shredded corn residues on the soil surface and disk-incorporated in the fallow year following corn production resulted in very little reduction in runoff compared with a bare soil surface, but soil losses were 54% lower with corn residues on the soil surface compared with bare soil. A laboratory study by Gilley et al. (1986) with corn residues also showed that residues

were less effective for reducing runoff than for reducing soil loss. In the semiarid area of north-central Oregon, runoff was reduced during fallow periods of a conventional till winter wheat–fallow system receiving 145 kg N ha⁻¹ per crop as manure for the previous 67 yr compared with the same system receiving 90 kg N ha⁻¹ per crop as commercial fertilizer (Williams, 2004). Williams (2004) concluded that using manure amendments and not burning residue from the previous crop maintained soil organic C levels that reduced or retarded runoff. That same data set provided evidence of reduced soil erosion with the use of manure and maintenance of wheat residue on the soil surface (Williams, 2008).

Small grain harvest methods can greatly influence residue amount and orientation, and subsequently soil water evaporation during the fallow period. McMaster et al. (2000) showed that soil water evaporation could be reduced by 20 to 50% as wheat harvest cutting height increased from 0.1 m to 0.5 m, with the amount of evaporation reduction during the fallow period being dependent on standing residue stem population. Under very low stem population conditions (a result of poor seedling emergence and/or poor growing season rainfall), the use of a stripper-header (Fig. 19|1) (Henry et al., 2008) was advised to increase standing residue mass and height to minimize soil water evaporation over the fallow period.

The combined effects of decreased runoff and evaporation through reduced tillage and increased surface residues during the fallow period lead to increased infiltration. Baumhardt and Lascano (1996) measured cumulative infiltration in winter wheat residue increasing from 29 mm with 0 Mg ha⁻¹ of residue to 47 mm with 2.5 Mg ha⁻¹ of residue in response to 65 mm of simulated rainfall applied over an hour. They noted the ability of surface residues to absorb raindrop impact and retard runoff. In a study on a sandy clay loam in southwestern Queensland, Thomas et al. (2008) reported increased surface residue resulted in increases in time to runoff, final infiltration rate, and cumulative infiltration following 100 mm of simulated rainfall

to wheat residues at the end of a 6-mo fallow period. Pikul and Aase (1995) reported greater infiltration in an annual wheat no-till system than in a wheat–fallow conventional till system during the first hour of the first day in which measurements were taken, but that this difference disappeared over the course of the infiltration run. They concluded that the sandy loam soil of the experimental area settled firmly following rainfall, with textural size components that effectively filled the available void spaces of the soil with solids causing surface sealing. Pikul et al. (2006) found no significant cropping system effects on infiltration for locations that had the same tillage system but differing cropping intensity or crop species in the cropping system. However, where no tillage was compared with tillage, infiltration was greater following tillage and declined over time in tilled systems. They cautioned that conclusions regarding cropping system effects on infiltration should be made carefully due to the significant temporal variation in infiltration rate measurements.

No-tillage, however, does not always result in the most infiltration from a given precipitation event (Unger, 1992; Jones and Popham, 1997). Infiltration may be greater into a tillage-loosened than a no-tillage soil when precipitation amounts do not exceed the temporary storage capacity of the loosened soil layer. Also, infiltration into a tillage-loosened soil may be greater when

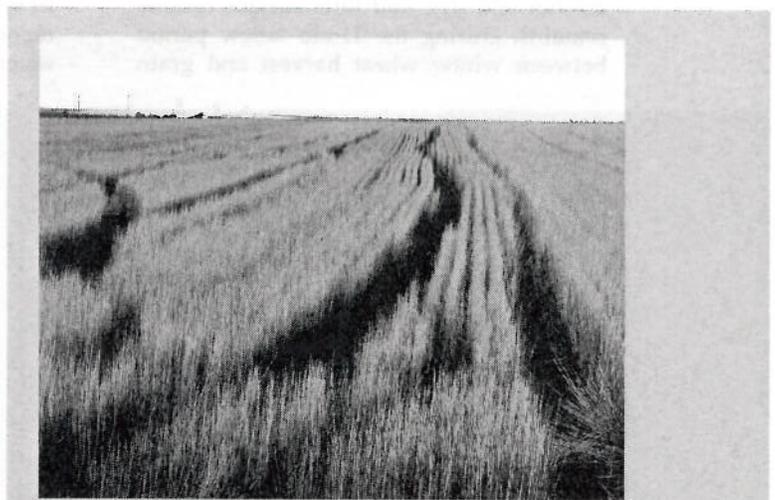


Fig. 19|1. Fallow wheat stubble following harvest with a stripper-header.

the water content of no-tillage soil is relatively high following precipitation, thereby resulting in slow infiltration and limited opportunity for additional water storage, which was the case on a Pullman clay loam (fine, mixed, thermic Torrertic Paleustoll) at Bushland, Texas (Jones and Popham, 1997).

An important fraction of the precipitation in parts of the central and northern Great Plains falls as snow (Fig. 19|2). Standing crop residues are more effective at reducing wind speed near the soil surface than flat residues (Siddoway et al., 1965; Bilbro and Fryrear, 1994) and therefore trap more snow during the winter period. Nielsen (1998) measured about 20 cm more stored soil water after winter in standing sunflower (*Helianthus annuus* L.) residue with a silhouette area index (residue height \times diameter \times population) of 0.07 m² m⁻² than where the sunflower stalks were lying flat on the soil surface. This was in response to greater snow catch by the standing sunflower stalks.

The final effect of decreased runoff, decreased evaporation, and increased infiltration in response to more surface residues during the fallow period is greater precipitation storage efficiency and increased available soil water at the end of the fallow period. Peterson et al. (1996) summarized data from several Great Plains studies that showed the inefficiency of precipitation storage in no-till fallow systems during the late portion of the summer fallow period, a time when the soil profile is at or near field capacity, daily weather conditions are hot and dry, and little surface residue remains. During the 11-mo fallow period between winter wheat harvest and grain

sorghum planting in the Texas Panhandle, Baumhardt et al. (1985) measured precipitation storage efficiency increasing from 22% under disk tillage to 31% under no-till management, which they attributed to evaporation suppression due to greater surface crop residues under no-till. Similar results have been reported at other Great Plains locations (Peterson et al., 1996; Smika, 1990; Smika and Wicks, 1968; Tanaka and Aase, 1987; Unger and Wiese, 1979; Lyon et al., 1998; Nielsen and Vigil, 2010). Available water at sorghum planting, following an 11-mo fallow period following after wheat harvest in Texas, was nearly 50 mm greater with 4 Mg ha⁻¹ of wheat residues on the surface compared with 0 Mg ha⁻¹ of surface residues (Unger, 1978). The 9-yr average available soil water at wheat planting at Akron, Colorado was 227 mm for no-till wheat-fallow systems and 156 mm for conventional till wheat-fallow systems (Nielsen et al., 2002). These results clearly indicate the effects of surface residue destruction and soil stirring on enhancing evaporation and decreasing precipitation storage efficiency when sweep plow tillage was used for weed control during the fallow period.

The effect of the fallow period frequency in a cropping system on available soil water was quantified by Nielsen et al. (2002) for winter wheat systems in northeastern Colorado. The 9-yr average available water content at wheat planting was 227 mm for a wheat-fallow system, but only 108 mm for the continuously cropped wheat-corn-millet system. Jones and Popham (1997) similarly reported a 10-yr average plant available soil water content at wheat planting at Bushland, Texas of 212 mm for wheat-fallow, 205 mm for wheat-sorghum-fallow, and 156 mm for continuous wheat.

The increased precipitation storage efficiency from the use of reduced and no-till systems for weed control during the fallow period of wheat-fallow systems in the central Great Plains has led to the implementation of more intensive cropping systems that reduce the frequency of fallow (Peterson et al., 1993; Anderson et al., 1999; Nielsen et al., 2002). If the increased soil water is not used by more intensive cropping systems that reduce the frequency of fallow,



Fig. 19|2. Snow deposition in fallow sunflower stalks.

water can move below the active root zone, taking with it N and potentially affecting groundwater quality. O'Connell et al. (2003) measured increased drainage below the root zone in a fallow system (fallow–wheat–pea [*Pisum sativum* L.]) compared with a system without fallow (mustard [*Brassica juncea* (L.) Czern.]–wheat–pea) in southeastern Australia. Introduction of fallow production methods in the semiarid areas of the Great Plains has sometimes led to the formation of saline seeps (Halvorson and Black, 1974) as water percolated below the root zone. This problem can be alleviated with the use of flexible crop rotations involving small grains, grasses, deep-rooted crops, and a minimum amount of summer fallow as crops are grown when sufficient soil water is present at planting to indicate likely successful crop production.

Effects on Nutrient Availability

Fallow enhances accumulation of nitrate through mineralization of organic matter (Smika, 1983a; Campbell et al., 1990). Cochran et al. (2006) stated that during the early years of crop production in the northern Great Plains, relatively high levels of organic matter supplied adequate nutrition as N mineralization was enhanced by aeration with tillage in conjunction with high soil moisture content during the fallow period. Prolonged cropping of these prairie soils depleted soil N such that fertilizer N is now required. Unger (1991) reported a nonsignificant tendency for a no-till wheat–sorghum–fallow system in Texas to have higher levels of N, $\text{NO}_3\text{-N}$, P, and K at the soil surface than the stubble mulch tillage system 6 to 8 yr after the systems were established. Mikha et al. (2006) found total soil N was significantly increased in the 0- to 7.5-cm depth by decreasing tillage and fallow frequency at several central and northern Great Plains locations. The effect of fallow tillage intensity on total N in the 0- to 7.6-cm depth in a wheat–fallow system in Texas was reported by Unger (1968). After 24 yr of management, 36% higher total N was found in the system where six to ten sweep tillage operations were delayed until the spring and summer following wheat harvest compared with the system where up to ten

fallow-period one-way disk operations were used to control weeds throughout the entire fallow period.

Fallow no-till systems can also increase P and other micronutrients in the upper layers of soil. Unger (1991) also reported approximately 60% higher extractable P in the 0- to 4-cm soil layer from a wheat–sorghum–fallow system under no-till management compared with stubble mulch management in Texas. Follett and Peterson (1988) showed tillage intensity effects on several nutrients from a loam soil in western Nebraska that had been in wheat–fallow production for 16 yr. They found that total P, organic P, K, Zn, and Fe in the 0- to 5-cm layer declined with increasing tillage intensity (no-till > stubble mulch > moldboard plow). They attributed these results mainly to cycling of nutrients to the soil surface in plant parts and subsequent residue that was then mixed and diluted with soil from lower depths as tillage intensity increased.

Bowman and Halvorson (1997) conducted a detailed study of the effect of fallow frequency on P in the 0- to 5-cm soil layer in northeastern Colorado. As fallow frequency was reduced from one crop in 2 yr to two crops in 3 yr to three crops in 4 yr to continuous cropping, water-soluble P, anion-exchange resin P, total soil organic P, phosphatase activity, soil bicarbonate-extractable organic P, and total P all increased. They attributed the increase primarily to greater residue production in systems with less fallow. The P uptake from deeper in the soil profile was deposited at the soil surface through greater residue and litter production and subsequent leaching of P from the residue and decomposition of the residue in contact with soil. Additionally, there was probably enhanced P protection from wind erosion as summer fallow was eliminated. Decreasing fallow frequency similarly increased levels of Zn, Mn, and Fe in the 0- to 5-cm layer but did not affect Cu or $\text{SO}_4\text{-S}$ levels (Bowman and Vigil, 2000).

Because crop water use generally exceeds precipitation in the semiarid regions that employ fallow systems, leaching of N beyond the root zone through downward water movement is rarely a loss mechanism for N (Ryan and Monem, 1998). In comparing fallow tillage systems in Queensland, Australia, Standley et al. (1990) found greater losses of N, P, S, and K in the surface 10 cm

of a vertisol after 7 yr of conventional tillage compared with no-till. They attributed the N losses to greater losses of NO_3^- leached below the 0.6-m sampling zone and greater denitrification with conventional tillage.

Effects on Soil Microbial Activity and Diversity

Soil microbes are important for the functioning of agroecosystems because they serve as catalysts of essential nutrient cycling conversions and are an important part of the labile C and N pools in soil (Paul, 2007). Because of this, reducing plant residue inputs through the use of fallow causes a decline in soil OM that starves soil microbes, which in turn limits the metabolic capacity and biological function of the soil. Steenwerth et al. (2002) showed that soil microbial biomass, measured by phospholipid fatty acid content, declined sharply in soils under conventional till fallow for 2 yr compared with adjacent cropped and grassland soils in California coastal valleys. Experiments at the Ultuna Long Term Soil Organic Matter Experiment in Uppsala, Sweden (clay loam soils, Typic Eutrochrept) showed that important soil microbial variables such as potential denitrification and basal soil respiration rate were reduced in conventional till fallow soils relative to cropped soils (Enwall et al., 2005). The conventional till fallow had less total soil C and N content compared with the cropped soils, and the lowest microbial biomass as measured by substrate induced respiration (Enwall et al., 2007). Enwall et al. (2007) found that bare fallow had low potential ammonia oxidation and a different ammonia oxidizer diversity relative to the cropped soils, possibly due to the reduced N mineralization and lack of N fertilizer in the fallow soil, showing that bare fallow can also affect soil microbial activity indirectly through changes in soil properties such as N availability and pH, brought about by the presence or absence of N fertilizer.

Liebig et al. (2006) summarized the findings of several Great Plains studies by stating that cropping systems with intensive crop sequences (reduced fallow frequency) and/or reduced tillage possess more soil microbial biomass, potentially mineralizable N, and total glomalin. Glomalin is a gel-like substance produced by mycorrhizal fungi

that has been linked to higher soil C and better soil structure (Wright et al., 1999). Those trends were attributed to greater crop residue, root mass, and soil OM accumulation in the soil surface of these systems. They also stated that in the Great Plains, no-till management during fallow compared with conventional tillage resulted in increased fungal abundance, higher populations of denitrifying bacteria, and greater ester- and phospholipid-linked fatty acid methyl esters, resulting in conditions favoring growth and activity of soil microorganisms that improve soil structure, but also increasing gaseous N loss by denitrification.

Residue management can have long-lasting effects on soil microbiology. Biederbeck et al. (2005) conducted a 6-yr study comparing the effects of green fallow–wheat rotations, bare fallow–wheat, and continuous wheat in a Canadian silt loam (Aridic Haploboroll). Bare fallow–wheat had 34% less residue dry matter inputs and 48% less residue N inputs than the continuous wheat system, resulting in a lasting negative effect of the bare fallow on soil microbes. Soil bacterial counts, microbial biomass, mineralizable C, and the soil enzymes dehydrogenase, phosphatase, arylsulfatase, and urease were lowest in the bare fallow–wheat relative to the rest of the treatments, even though the soils were sampled after the wheat phase of the rotation. In contrast, the green-fallow systems, in which the legumes were grown to full bloom and then incorporated, had a positive effect on microbial counts, microbial biomass, and enzymes relative to bare fallow–wheat and continuous wheat.

Agricultural practices can affect the soil microbiological abundance and diversity indirectly by altering physical and chemical properties, which in turn can alter the immediate environment of soil microbes and cause shifts in microbial community composition (Paul, 2007). Steenwerth et al. (2002) studied soil microbial community composition on loam soils in California under irrigated and dryland management, annual and perennial grassland, and bare fallow. The fallow sites were previously annual grasslands that were tilled and then kept bare for 2 yr using herbicides. Total soil C and N (0- to 6-cm depth) suffered losses of 20 and 34% respectively due to the lack of C inputs and mineralization of soil OM during fallow. Phospholipid

fatty acid analysis indicated that microbial community structure diverged from that of the adjacent grassland sites, partly due to increased abundance of Gram-negative bacterial markers.

Exceptions do occur, showing that not all microbial functions are equally sensitive to fallow. Enwall et al. (2005) showed that bare-fallow soils had similar genetic fingerprints as unfertilized cropped plots, indicating that fertilizer addition and pH may be more important drivers of microbial diversity than the presence or absence of plants in the soils studied.

The reduced C inputs in bare fallow can have negative effects on soil function through the reduction of microbial enzymes. Pankhurst et al. (2005) compared three crop break treatments—pasture, alternate crops, and bare fallow—as alternatives to continuous sugarcane in Queensland, Australia. The microbial biomass C decreased up to 43% and total free-living nematodes decreased up to 14% under bare fallow relative to continuous sugarcane. Interestingly, the soil microbial community of the bare-fallow break had a reduced capacity to utilize different C substrates than the soil microbial community under sugarcane, indicating a clear effect on soil microbial function in the absence of plant cover.

Weigand et al. (1995) investigated microbial C, catalase activity, and earthworm abundance in soils from different sites in Bavaria maintained under bare fallow for 6 yr. Microbial C was strongly correlated with soil organic C and with soil catalase (an important enzyme for aerobic metabolism). The soils under bare fallow, with no rhizodeposition or residue input, had less microbial biomass and lowered efficiency of microbial C metabolism as measured by substrate induced respiration.

Acosta-Martinez et al. (2007) showed that cropping intensity affected soil microbial composition and enzyme activity in long-term plots in northeastern Colorado. The study aimed to find more efficient alternatives to the traditional wheat-fallow common in the region. Increased fallow frequency coupled with conventional tillage was associated with reduced soil microbial biomass and soil enzymatic activity. Fatty acid methyl ester analysis indicated that the plots under the more intense rotations also had a different soil microbial community

structure than the wheat-fallow plots, as well as reduced fungal abundance in the wheat-fallow treatment.

Bare fallow can have a direct effect on obligately symbiotic organisms such as arbuscular mycorrhizal fungi that depend entirely on certain plant roots for their energy. The long-fallow disorder occurs when mycorrhizal fungal inoculum declines during a bare-fallow period because of the absence of active crop roots (Thompson, 1987; Hulugalle et al., 1998; Pankhurst et al., 2005). Mycorrhizae can benefit row crops by increasing P and water uptake, so the bare fallow can potentially result in reduced performance in subsequent crops. However, P and Zn fertilizer help alleviate the long-fallow effect by reducing nutrient deficiency and promoting mycorrhiza formation. Oliveira and Sanders (1999) observed the long-fallow effect on low-P soils in Leeds, England. As expected, fallow soils had lower mycorrhizal infectivity than recently cropped soils. Interestingly, prior cropping with a strongly mycorrhizal plant (*Zea mays* L.) increased infectivity relative to a wheat pre-crop, suggesting a strategy to minimize the negative effect of the fallow on mycorrhizal infection.

Bare fallow can also affect soil pathogenic microorganisms by removing the host crops, reducing crop residues, and changing the soil physical environment in such a way that the pathogen life cycles are disrupted. Hulugalle et al. (1998) compared long-fallow cotton (*Gossypium* L.) with continuous cotton in New South Wales, Australia. The long-fallow cotton affected the soil physical properties by reducing soil strength and plastic limit, and black root rot was lower during the cotton phase after long fallow. *Fusarium* fungi can cause important economic losses in crops because *Fusaria* can infect the xylem of the plant and cause head blight, root rot, crown rot, and seedling blight in several crop species. Contaminated crop residues are an important source of *Fusarium* propagules (Dill-Macky and Jones, 2000), so crop rotations and residue management are important options to control disease. Sturz and Johnston (1985) found that pathogenic *Fusaria* are found on stubble in soil, and tend to be in higher amounts in soils under continuous cropping than in bare-fallow soils due to the differences in crop residue. Because of this, they suggest

fallowing as a strategy to control *Fusarium* in barley (*Hordeum vulgare* L.) and wheat in Canada.

Rhizoctonia fungi are root pathogens that can cause important economic losses due to root infection and seedling damping-off. Like *Fusarium*, *Rhizoctonia* normally survives saprophytically in plant debris and plant tissues before it infects a crop. However, Bell and Sumner (1987) demonstrated that *Rhizoctonia sclerotia* can survive for more than 40 wk in fallow soils without plant cover or fresh residues, and remain viable to infect corn afterward. The authors suggest that a bare fallow alone will not be effective in controlling *Rhizoctonia*, and that tillage or mulching with polyethylene will be required in addition to fallow for effective control. It is not surprising, then, that chemical fallow periods of up to 66 d were not effective in the control of *Rhizoctonia* in wheat grown in Western Australia (MacNish and Fang, 1987). In a study about carrot (*Daucus carota* L.) damage in the Central Valley of California, populations of *Rhizoctonia* and *Pythium* were similar following fallow, onion (*Allium cepa* L.), or carrots (Davis and Nunez, 1999). Like *Rhizoctonia*, other fungal pathogens such as *Sclerotium rolfsii* Sacc. produce resistant sclerotia, giving them the capacity to survive for prolonged periods of time in soil (Coley-Smith and Cooke, 1971), and it is possible that a fallow period will not be completely effective for their control.

Rotations with resistant crops and residue removal can be better than fallow for the control of root pathogens under some conditions. Johnson et al. (1997) studied the effectiveness of bare fallow and sod to suppress nematodes, *Pythium*, and *Rhizoctonia* on vegetable crops in a Tifton loamy sand (fine-loamy, siliceous, thermic Plinthic Paleudults). The plant parasitic nematode, *Rhizoctonia*, and *Pythium* numbers as well as *Fusarium* damage, were lower on vegetable crops preceded by sod than on plantings after fallow. Smiley et al. (1996) studied wheat diseases in wheat-fallow, wheat-pea, and continuous wheat in a Walla Walla silt loam (coarse-silty, mixed, mesic Typic Haploxeroll) near Pendleton, Oregon. *Rhizoctonia* root rot, *Pythium* root rot, eyespot, and take-all were suppressed by burning crop residues following harvest. These diseases can survive on infected crop residues, so removing the residue via burning lowers

the incidence of disease in subsequent crops. Furthermore, crown rot increased with surface residue. Eyespot and crown rot were exacerbated by soil N and declined with soil pH. In this case, rotating crops was a good disease management strategy. In general, diseases were less damaging on the wheat-pea rotation relative to the continuous wheat and the wheat-fallow. Replacing chemical fertilizers with green manure and animal manure was also beneficial in suppressing soil-borne diseases.

Effects on Erosion

As stated earlier, standing residue is more effective than flat residue for decreasing wind speed near the soil surface, and consequently in controlling wind erosion. The standing residue absorbs more of the wind's energy and raises the zero-velocity point above the soil, thereby preventing much of the normal avalanching of soil material downwind (Woodruff et al., 1972; van de Ven et al., 1989). Smika (1983b) measured a 74% reduction in wind speed at the soil surface when standing wheat residue height was increased from 30 to 61 cm. Consequently, there may be significant differences in soil erosion during fallow periods depending on residue amount, type, quality, and orientation.

Nielsen and Aiken (1998) showed that a silhouette area index of 0.035 to 0.045 m² m⁻², achievable through leaving sunflower stalks standing during the fallow period following harvest (Fig. 1913), can reduce saltation discharge to less than 5% of that predicted for bare surfaces. A silhouette area index of 0.04 m² m⁻² would be achieved with a stem population of 40,000 stems ha⁻¹, stem diameter of 1.75 cm, and stem height of 57 cm. Typical values of silhouette area index for standing wheat (0.54 m² m⁻²; McMaster et al., 2000) and proso millet (0.08 m² m⁻²; Henry et al., 2008) residues following harvest are well above the 0.04 m² m⁻² value, indicating that those small grain residues left standing will reduce erosion potential to nearly zero as they remain standing during the fallow period. The use of a stripper-header for the harvest of small grains leaves significantly more standing crop residues that will be retained longer than residues following grain harvest conventionally cut with a sickle-bar header (Henry et al., 2008). The

result is more protection of the soil from wind erosion and greater precipitation storage efficiency during fallow periods.

Sharratt et al. (2007) quantified soil loss from conventionally tilled silt loam fallow fields (winter wheat–fallow system) in the Columbia Plateau of eastern Washington. Six high wind events occurred over a 2-yr period resulting in soil loss ranging from 43 to 2320 kg ha⁻¹ per wind event and PM10 loss ranging from 5 to 210 kg ha⁻¹ per wind event. The PM10 loss comprised 9 to 12 per cent of the total soil loss. They concluded that alternative tillage practices or cropping systems were needed for minimizing PM10 emissions and improving air quality in that region. Similar magnitudes of soil losses through wind erosion have been reported for silt loam soils in Colorado (Van Donk and Skidmore, 2003) and in Washington (Zobeck et al., 2001), but much higher losses (12,000 to 56,000 kg ha⁻¹) have been reported for sand and sandy loam soils in other locations (Zobeck et al., 2001; Larney et al., 1995). The higher soil losses may also be related to differences in wind event speed and duration, surface roughness, or surface cover. Using the wind erosion prediction system (WEPS; Hagen, 1991), Feng and Sharratt (2007) estimated an annual soil loss of 14,250 kg ha⁻¹ from summer fallow fields in eastern Washington.

Soil loss under fallow management due to water erosion can also be significant. Boellstorff and Benito (2005) described the increase in bare (unseeded) fallow area in Europe that occurred following the adoption of the 1992 MacSharry reforms to the European Union's Common Agricultural Policy that included a set-aside program requiring farmers to take certain percentages of arable land out of production. In central Spain, even areas with sufficient precipitation to support seeded fallow with a cover crop were being put into traditional unseeded fallow with tillage. A study involving the use of the revised universal soil loss equation (RUSLE; Renard et al., 1991) indicated the use of seeded fallow in central Spain would cut the area estimated to have greater than 6 t ha⁻¹ soil loss to one-third the area under that risk when in unseeded fallow (Boellstorff and Benito, 2005). In central Croatia, Basic et al. (2004) measured a 5-yr average soil loss of 87 t ha⁻¹ from standard bare fal-



Fig. 19|3. Anemometers in fallow sunflower stalks.

low USLE protocol plots (Wischmeier and Smith, 1978) on a 9% slope.

Summary

Fallow production systems continue to be used throughout various regions of the world, but particularly in semiarid regions where precipitation is highly variable in timing and amount. Systems that reduce or limit fallow frequency and tillage intensity generally result in greater amounts of surface crop residues remaining during fallow periods. Those residue increases generally produce positive effects on soil quality for crop production, including increases in soil OM, nutrients, physical structure, water content, and microorganisms, as well as reductions in soil loss by wind and water erosion.

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