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Review

North American Soil Degradation: Processes, Practices, and Mitigating Strategies

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Abstract: Soil can be degraded by several natural or human-mediated processes, including wind, water, or tillage erosion, and formation of undesirable physical, chemical, or biological properties due to industrialization or use of inappropriate farming practices. Soil degradation occurs whenever these processes supersede natural soil regeneration and, generally, reflects unsustainable resource management that is global in scope and compromises world food security. In North America, soil degradation preceded the catastrophic wind erosion associated with the dust bowl during the 1930s, but that event provided the impetus to improve management of soils degraded by both wind and water erosion. Chemical degradation due to site specific industrial processing and mine spoil contamination began to be addressed during the latter half of the 20th century primarily through point-source water quality concerns, but soil chemical degradation and contamination of surface and subsurface water due to on-farm non-point pesticide and nutrient management practices generally remains unresolved. Remediation or prevention of soil degradation requires integrated management solutions that, for agricultural soils, include using cover crops or crop residue management to reduce raindrop impact, maintain higher infiltration rates, increase soil water storage, and ultimately increase crop production. By increasing plant biomass, and potentially soil organic carbon

(SOC) concentrations, soil degradation can be mitigated by stabilizing soil aggregates, improving soil structure, enhancing air and water exchange, increasing nutrient cycling, and promoting greater soil biological activity.

Keywords: soil erosion; compaction; salinization

1. Introduction

Soil degradation describes ongoing processes that generally limit agronomic productivity, result in undesirable or deteriorating physical, chemical or biological properties, enhance soil displacement due to wind or water driven erosion [1], and require reassignment of land resources. Soil degradation often interacts with terrain and climatic factors defining an ecosystem to reduce sustainable land productivity, which, eventually, threatens food security. Common examples of chemical and physical *in-situ* soil degradation include compaction (due to heavy machinery or repeated tillage operations), systematic loss of aggregate stabilizing soil organic matter (SOM), and soil salinization or acidification as a result of problematic drainage, nitrification, or chemical contamination. The greatest soil degradation threat, however, is wind- or water-induced erosion that displaces soil and depresses land productivity, and results in deteriorated physical properties, nutrient losses, and reshaped, potentially unworkable, field surface conditions. Both *in situ* deterioration and soil erosion are frequently a consequence of using unsuitable management practices because soil resource and climatic constraints are not well understood. A classic example in the semiarid Great Plains was the 1930s Dustbowl.

Two other human-induced causes of *in-situ* soil degradation and its resultant reduction in land productivity are industrial dislocation through mining operations and urban sprawl. The latter usually imposes no chemical or physical deterioration, but typically results in the irreversible reassignment of land resources for construction of housing and infrastructure as necessitated by population growth and related commerce. In the U.S., urban land use has increased by 400% from 6 to 24 million ha since 1945; however, this only accounts for ~3% of total land resources [2]. A larger critical issue associated with urban sprawl is that the continued expansion of infrastructure, such as interstate highway development currently exceeding 75,000 km, can promote suburban growth and results in agricultural land losses at a rate of ~120 ha for each added kilometer of interstate [3]. Soil degradation by land reassignment for urban growth is beyond the scope of this article, but redevelopment of existing urban land can conserve soil resources and have multiple additional benefits of rectifying traffic congestion and crime. For example, in 1982, decades after its 1890 establishment, Lubbock, Texas, redeveloped dilapidated and abandoned housing of one original ~130 ha residential area to partially meet housing needs of the growing ~300,000 population. That necrotic urban area, once occupied by 2% of the municipal population with 28% of the crime [4], now benefits from decreased crime, e.g., ~90% fewer burglaries than in 1983. Urban sprawl was delayed and Lubbock taxable property values increased from pre-redevelopment \$27 million to \$750 million upon eventual completion [5].

Mining to extract minerals, coal, or oil and gas is common throughout North America with methods that vary from open pits, as used for oil sands in Canada, to mountain top removal for coal from some Appalachian states [6]. In 2007, mined areas of the contiguous U.S. were included in ~27 million ha of miscellaneous land or 3% of the total land [2], but an earlier listing of mining activities by Lal *et al.* [7] estimated the disturbed area to be 4.4 million ha. Surface mining regulations in most of North America require topsoil and spoil reclamation to reverse soil degradation and approximate pre-mining conditions; however, the U.S. "Comprehensive Environmental Response, Compensation and Liability Act" of 1980 or Superfund targeted cleanup of related hazardous waste sites [8]. Superfund sites are replete with abandoned mineral mining and smelting locations [9] that introduce acidic water contaminated with various heavy metals into streams and the surrounding soil. Herron *et al.* [10] described successful site remediation that integrated multiple steps ending with revegetated soil caps protected by runoff diversion ditches for rainfall management (Figure 1). Mine related soil degradation also affects remote locations after land application of contaminated sediments that render treated land difficult to revegetate without amendments to correct reduced soil conditions and contaminant solubility [11].

Figure 1. Mine spoil mitigation after installing soil cap that is protected from further contamination by stormwater runoff using collection and diversion channels.

Although soil resources can be degraded in many ways, our goal is to examine the problem from an agronomic perspective. The history of soil degradation in North America includes the catastrophic wind erosion during the 1930s U.S. Dust Bowl [12] and followed devastating water erosion in the southeastern U.S. referred to in 1910, for one example, as the Badlands of Mississippi [13]. Nevertheless, human recognition of soil degradation is very slow as evidenced by the 1909 U.S. Bureau of Soils Bulletin 55 described the soil resource as an "indestructible, immutable asset" [14]. That perception of the soil resource coupled with unsuitable production methods implementing repeated tillage to promote greater rain infiltration and, for semiarid production, to develop an evaporation limiting dust mulch [15] led to massive soil erosion losses during the Dust Bowl. Soil salinization as a result of irrigation together with compaction and the reduction of organic carbon due to tillage management practices represent consequences of still other agents that have degraded the soil productivity.

Achieving the goal of sustainable management practices that remediate or prevent soil degradation requires a better understanding of interacting environmental conditions, production methods, and land resources. Soil degradation has been the topic of comprehensive reviews for over a quarter century and many correlated these interacting factors. Admittedly the nature of soil management and degradation is site-specific, but we submit that almost globally universal soil degradation agents will lead to common best management practices. Therefore, our objective is to highlight problematic process agents and successful integrated management solutions for mitigating and restoring the soil resources such that a management perspective meeting mutual soil stewardship goals may emerge.

2. Processes and Practices Associated with Soil Degradation

2.1. Tillage

The primary purpose of agriculture is to secure food resources, which has long relied on efforts to advance agricultural technology, ranging from preparing a seed bed with tillage sticks for improved soil contact to applying water by irrigation for stabilized crop production. In North America, advances in tillage technology can be traced to Thomas Jefferson's 1784 soil inverting "moldboard plow" design that John Deere produced and marketed during the 1830s [16]. Tillage was historically considered a beneficial practice that was generally considered necessary for weed control, preparing an ideal seedbed, and for increasing water infiltration. Good tillage was associated with good farming and became a revered part of the culture of agriculture [17] as exemplified by the seal of the U.S. Department of Agriculture contains a picture of a moldboard plow.

Although not mentioned as a benefit, tillage generally increased soil fertility by hastening the decomposition of soil organic matter (SOM) so N, P, K, S, and other nutrients required for plant growth are mineralized to forms that are readily available for use by plants. In contrast to the positive benefits that tillage has for soil fertility, the accelerated SOM loss ultimately contributes to increased soil erosion, loss of soil structure, decreased biological activity, and other factors that lower soil quality.

Tillage technology advanced rapidly in response to farm mechanization, including internal combustion powered tractors in the 1920s [18]. That is, when farm mechanization eliminated the need for animal traction it concurrently eliminated demand for pasture and forage production supporting the displaced draft animals. In lieu of the draft animal limits imposed on cultivated area that an individual farmer could manage, mechanization greatly expanded the amount of land exposed to soil degradation through tillage.

2.2. Degradation of Soil Organic Matter

The inherent amount of SOM in soils varies greatly depending on soil texture and environmental conditions. Agricultural soils in North America at the time they were developed from grass prairies or forestland had SOM concentrations ranging from ~1% to 10% (*w/w*). Although variable, the slowly decomposable portion of SOM, often called humus, contains 58% C and has a C/N ratio of 12/1, a C/P ratio of 50/1, and a C/S ratio of 70/1 [19]. Himes [19] estimated only 35% of the C in crop residues returned to soil was sequestered in the soil as humus. This is considerably higher than the 17% to 18% determined by Rasmussen and Albrecht [20] for wheat (*Triticum aestivum* L.) residues in dryland soils in Oregon but similar to the 35% they found for manure. Rasmussen and Albrecht [20] also showed in a 30-year study that soil organic matter declined under annual cropping of wheat even when N fertilizer was added, but the decline was not as great with N additions.

These studies [19,20] show why it is important to understand that while SOM is largely comprised of organic C, SOM also contains other elements such that the sequestration of C as SOM requires the simultaneously sequesters other elements. While the decomposition of SOM results in a loss of C from the system as CO_2, the other elements (*i.e.*, N, P, and S) are not immediately lost from the system. These elements not only become available for plant uptake and removal with harvested products, but also for potential loss through erosion and leaching depending on the particular element, and by denitrification in the case of N. Thus, sufficient nutrients may not be available for restoring soil organic matter when increasing C sources. Using the estimates of Himes [19], the decomposition of 1% soil organic carbon (SOC) from the top 15 cm of a soil would result in a loss of 12,992 kg ha^{-1} C from the soil as CO_2, but 1082 kg of N, 260 kg of P, and 186 kg of S would have been converted from organic compounds to inorganic compounds.

The SOM content of many soils in North America is only about 50% of the level present at the time they were converted from forests or prairies to farm lands. Many forest lands in the U.S. contained 6% (*w/w*) or greater SOM and the grasslands of the U.S. and Canada contained from 1% to more than 6% SOM depending on the texture and environment. Cultivation increases soil aeration that accelerates biological activity resulting in rapid losses of C as CO_2 and mineralization of N, P, K and other plant nutrients. Therefore, the degradation of SOM was responsible for supplying the more than ample amounts of N, P, S and other nutrients needed for crop production when North America was settled.

One major management practice that limits SOM in semiarid dryland cropping systems on the Great Plains is the use of fallowing to conserve soil water, control weeds, release plant nutrients, and increase succeeding crop yields [21]. Fallowing limits the amount of crop residue produced and returned to the soil. Additionally, SOM mineralization may be enhanced by greater microbial activity as a result of increased soil water and temperature [22]. In the northern Great Plains, conventional tillage (CT) of the wheat-fallow (WF) system has resulted in a decline of SOM by 30% to 50% of their original levels in the last 50 to 100 year [23]. Because fallowing also reduces annualized crop yields, Aase and Schaefer [24] concluded that the system had become inefficient, unsustainable, and uneconomical. A 30-year dryland cropping system study conducted to quantify the effects of tillage, cropping, and fallow on SOC to a depth of 120 cm in Culbertson, MT showed that most of the response was observed in the surface 0–7.5 cm layer and that tillage did not influence SOC (Figure 2). Conventional tillage with a spring wheat-fallow system (CT-WF), however, reduced SOC at 0–7.5 cm by 25% to 30% compared to continuous spring wheat (CW) under CT or no-till (NT), management or CT-CW and NT-CW, respectively (Figure 2A). The yearly rate of SOC decline within the 0–7.5 cm layer was almost double in CT-WF compared with in NT-CW and CT-CW (Figure 2B). Alternate-year fallow, therefore, can reduce SOC in the surface layer more rapidly than tillage in dryland cropping systems in the northern Great Plains. A similar study by Rasmussen and Albrecht [20] showed that SOM levels in dryland fallow systems could be increased by adding manure except when fallow was included in the rotation.

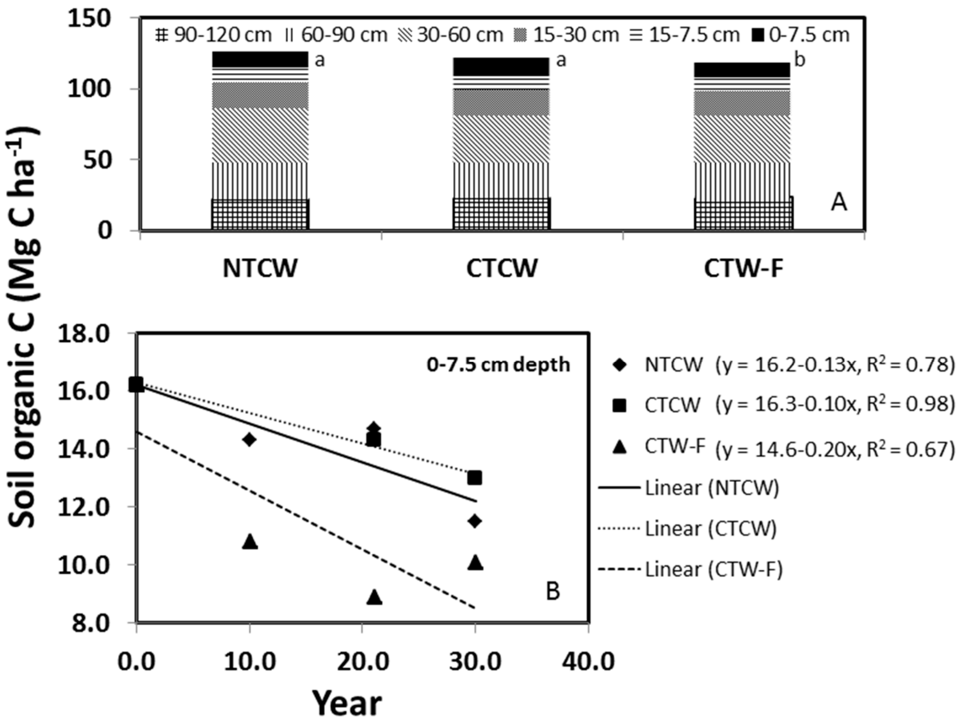

Figure 2. Effect of thirty years of tillage and cropping sequence on (**A**) soil organic C (SOC) contents at the 0–120 cm and (**B**) decline of SOC at 0–7.5 cm with year in dryland cropping systems in a field site, 10 km north of Culbertson, MT. NT-CW denotes no-till continuous spring wheat; CT-CW, conventional till continuous spring wheat; and CT-WF, conventional till spring wheat-fallow. Numbers followed by different letters at a depth in the bar are significantly different at $P = 0.05$ by the least square means test.

2.3. Degradation of Soil Physical Properties

Degradation of soil physical properties is closely linked to the loss of SOM because it serves as the glue to hold soil particles together to form aggregates. Aggregates provide structure that makes soils more resistant to erosion and compaction and increases the amount of plant available water they can hold. Hudson [25] showed that the volume of water held at field capacity decreased 3.6% (*v/v*) for each 1% decline in SOM. In all texture groups, decreasing the SOM content from 3.0% to 0.5% subsequently decreased the plant available water capacity by more than 50%. The loss of SOM also decreased the infiltration rate so that runoff increased, particularly during high intensity precipitation events. This resulted in water erosion as well as storing less water in the soil profile for plant use. The loss of SOM also makes the soils more vulnerable to wind erosion because individual soil particles are smaller and much more subject to erosion than aggregates.

Tillage incorporates plant residues but also disrupts aggregates, exposes new soil to wet-dry and freeze-thaw cycles, and affects microbial communities [26]. Tillage is more disruptive of larger aggregates, making SOC and soil N from larger aggregates more susceptible to mineralization [27,28]. Because particulate organic matter (POM) found in large aggregates is the main substrate for microorganisms, reduction in POM due to tillage can severely reduce soil aggregation [27,28]. Sainju *et al.* [29] concluded that fallowing reduces soil aggregation compared to continuous cropping by decreasing the amount of crop residue returned to the soil and by increasing soil organic matter mineralization due to enhanced microbial activity.

Soil organic matter is crucial to soil productivity because it affects soil physical, chemical and biological properties [23,27,30] including bulk density, aggregation, water holding and infiltration capacities, carbon sequestration, nutrient cycling, and microbial biomass and activity. Conventional tillage reduces SOM by disturbing soil and increasing aeration, which subsequently increases mineralization of SOC and soil organic nitrogen (SON) formed after incorporating crop residue [27]. Because of residue incorporation, Clapp *et al.* [31] observed that SOM level in Minnesota can occasionally be higher in subsurface than surface layers under conventional tillage compared with no-tillage.

Crop selection also influences soil aggregation. Soils from fields with legumes or bare soil will generally have smaller aggregates than from fields with non-legume vegetative cover. This occurs because lower amounts of crop residue are generally being returned to the soil and due to variation in the C/N ratio of residue. Crop residues with low C/N ratio decompose more rapidly than those with higher C/N ratio [32]. Sainju *et al.* [32] also noted that soil aggregation can also be lower in the surface than subsurface soils. Monoculture cropping systems can also reduce soil aggregate stability compared with diversified crop rotations [33]. Residue removal can also reduce soil aggregation, aggregate stability, macroporosity, aeration, and water infiltration compared with nonremoval [34].

Continuous monocropping can reduce crop yields due to greater disease and pest inoculum [35] that may, consequently, reduce the amount of residue returned to the soil for SOM [30]. The overall effect of N fertilization on SOM varies from increased levels due to greater biomass production and residue returned to the soil [36] to similar or decreased SOM due to increased mineralization as a result of reduced C/N ratio [37]. Removing residue for bioenergy production and by burning can seriously reduce SOM, since 5.2 to 12.5 Mg ha^{-1} of residue is needed to maintain SOC, depending on soil and climatic conditions [34,38].

2.4. Soil Degradation through Wind and Water Erosion

Wind and water erosion in North America increased rapidly with the expansion of cropland. In response, one of the most effective conservationists who sought to build public concern regarding soil erosion was Hugh Hammond Bennett. Often referred to as the "father of soil conservation," Bennett co-authored the highly influential publication entitled "Soil Erosion: A National Menace" [39] that influenced Congress to create the first federal soil erosion experiment stations in 1929 [40]. With the election of Franklin D. Roosevelt as President in 1932, conservation of soil and water became a national priority in the New Deal administration. The Soil Erosion Service was established in the Department of Interior in September 1933 with Bennett as Chief. The Soil Erosion Service established water erosion demonstration projects in critically eroded areas across the country to show landowners the benefits of conservation. Bennett's ability to influence public opinion is often illustrated by his effectiveness in getting support from the U.S. Congress. Beginning in 1932, persistent drought conditions throughout the Great Plains caused widespread crop failures resulting in serious wind erosion. A large dust storm on 11 May 1934 swept fine soil particles over Washington, D.C. and three hundred miles out into the Atlantic Ocean. More intense and frequent storms swept the Plains in 1935. On 6 March and again on 21 March, dust clouds passed over Washington and darkened the sky just as Congress commenced hearings on a proposed soil conservation law. Bennett seized the opportunity to explain the cause of the storms and to offer a solution. He penned editorials and testified to Congress urging the creation of a permanent soil conservation agency. The result was the Soil Conservation Act (PL 74-46), which President Roosevelt signed on 27 April 1935, creating the Soil Conservation Service (SCS) in the USDA [40]. In 1994, Congress changed SCS's name to the Natural Resources Conservation Service (NRCS) to better reflect the broadened scope of the agency's concerns.

Water erosion is dominant in the eastern portion of North America because of higher precipitation, but in the central and western areas where precipitation is lower and wind speeds are higher, wind erosion dominates. Figure 3 illustrates the areas in the U.S. where wind and water erosion rates are high enough that control practices are needed to minimize or prevent soil degradation.

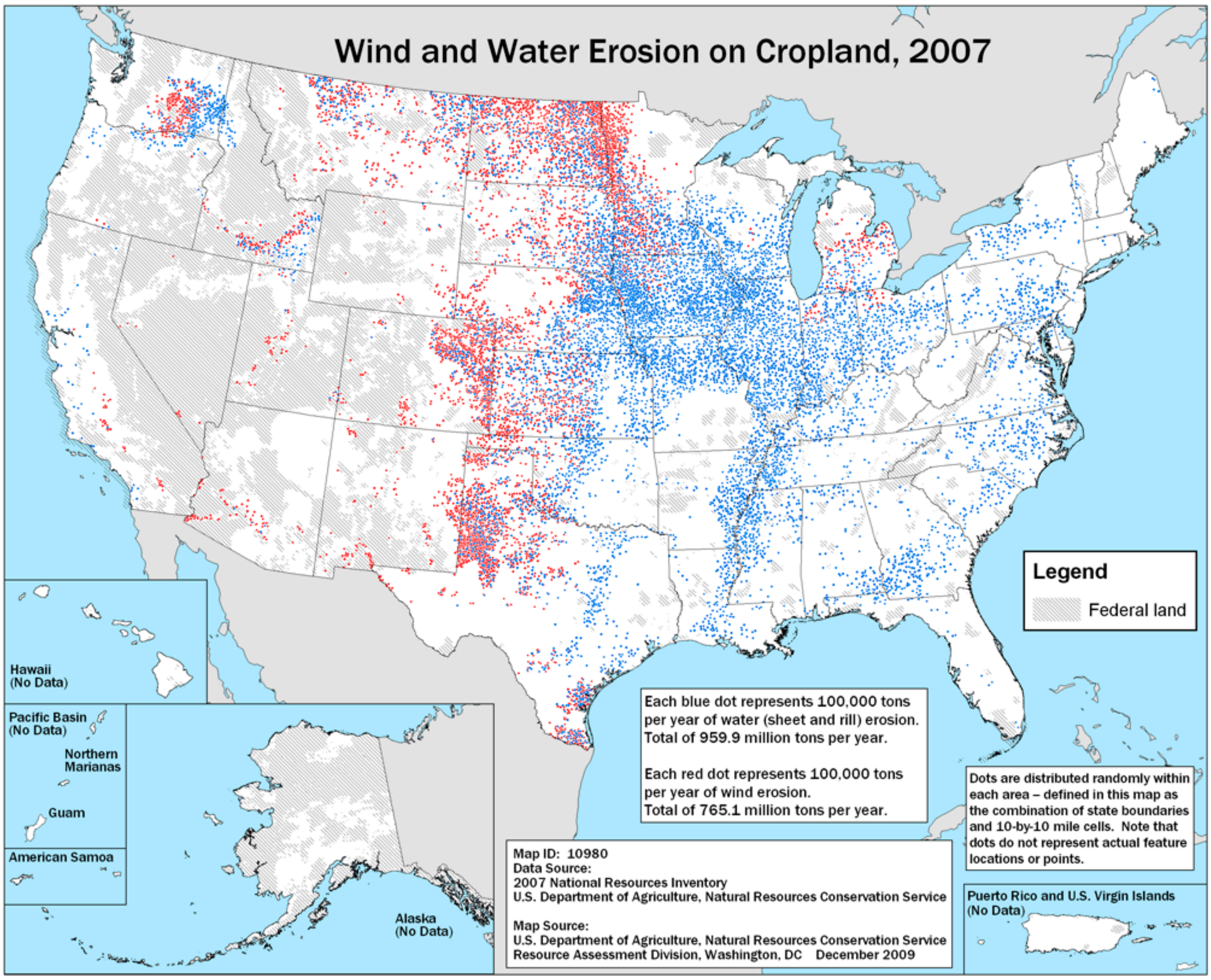

Figure 3. Distribution and amounts of water and wind erosion in the U.S. [41].

Soil degradation due to either wind or water is inextricably linked to loss of SOM. As a result, SOM in many North American soils have decreased by 30% to 40% [42], but with few exceptions, most croplands have been in crop production long enough that new equilibriums have been reached and SOM levels are no longer decreasing. In fact, several soils are showing some SOM increase, particularly where large amounts of crop residues are produced and limited or no tillage is used.

Soil organic matter consists of different pools of carbon compounds and some are considerably more active meaning that they are more amenable to decomposition processes. The major pools of SOM in virgin soils are often separated into plant residues, active SOM, and passive SOM as described by Brady and Weil [42]. Increases in SOM thus reflect greater amounts of C being added to the soil through larger root systems and more plant residue; two critical inputs causing SOC to reach a new equilibrium or even increase when tillage intensity is reduced. Finally, the large losses of SOM in North American soils, since they were converted to croplands, have reduced their inherent quality and productivity; crop yields on these soils have markedly increased because other factors (*i.e.*, improved cultivars, weed control, insect control, commercial fertilizers, and seeding methods) have more than offset SOM losses due to soil degradation.

2.5. Chemical Degradation

Chemical soil degradation can occur in response to various processes. Three principal consequences include: nutrient depletion, acidification, and salinization that are often associated with agricultural production systems. A fourth, contamination by heavy metals, industrial wastes, or radioactive material can be important, but is outside the scope of this contribution.

2.5.1. Nutrient Depletion

Declining SOM that depresses N mineralization will concomitantly decrease availability of P, K, and other nutrients and, for intensive crop production, increase dependence on fertility management or rotation alternatives depending on tillage. For example, Sainju *et al.* [29] reported that SOC, SON, and potential N mineralization were lower in CT-WF than NT-CW and CT-CW after 21 year in dryland cropping systems in eastern Montana although NO_3-N content was higher. Long-term nonlegume monocropping reduced N mineralization compared to crop rotation containing legumes and nonlegumes [43]. In other, long term rotation studies with sorghum (*Sorghum bicolor* (L.) Moench) and corn (*Zea mays* L.) summer crops, CT reduced soil Bray-P and cation exchange capacity at 0–5 cm compared with NT after 27 year under dryland spring wheat-sorghum/corn-fallow in Nebraska [44]. After 30 year of continuous wheat in Montana, tillage did not influence soil chemical properties (NT-CW *vs.* CT-CW) at 0–7.5 and 7.5–15 cm depth (Table 1) compared with the less intensively cropped CT-WF that, except for Ca and Mg, had generally lower values at 0–7.5 cm. The amount of nutrients removed through grain harvest can be higher in NT-CW and CT-CW than CT-WF due to increased cropping intensity and annualized yield [29,45]. Studies from the U.S. Corn Belt have shown that removing the residue for hay or bioenergy can have a similar adverse effect on soil fertility because residues contain plant nutrients that if not replaced have been shown to decrease crop yields [46] by as much as 1.8 to 3.3 Mg ha^{-1} after 50% to 100% straw removal [34].

Table 1. Effect of 30 years of tillage and cropping sequence combination on soil chemical properties under dryland spring wheat system in a field site, 10 km north of Culbertson, MT.

Chemical property	Soil Depth (cm)	Treatment †		
		NT-CW	CT-CW	CT-WF
Olsen-P (mg kg^{-1})	0–7.5	36.8 a ‡	40.0 a	25.0 b
	7.5–15	2.8 a	5.5 a	4.9 a
K (mg kg^{-1})	0–7.5	331 a	331 a	272 b
	7.5–15	279 a	282 a	186 b
Ca (mg kg^{-1})	0–7.5	989 b	894 b	1294 a
	7.5–15	1597 a	1606 a	2359 a
Mg (mg kg^{-1})	0–7.5	212 b	193 b	253 a
	7.5–15	340 b	350 b	433 a
Na (mg kg^{-1})	0–7.5	14.5 a	14.8 a	12.4 b
	7.5–15	14.4 a	14.3 a	15.5 a
SO_4-S (mg kg^{-1})	0–7.5	6.8 a	6.3 a	8.0 a
	7.5–15	3.5 a	3.5 a	8.1 a
Cation exchange capacity ($cmol_c$ kg^{-1})	0–7.5	14.3 a	14.5 a	11.9 b
	7.5–15	11.6 a	12.9 a	15.9 a

† Treatments are NT-CW, no-till continuous spring wheat; CT-CW, conventional till continuous spring wheat; and CT-WF, conventional till spring wheat-fallow; ‡ Values within a row followed by the same letter are not significantly different at $P = 0.05$ according to the least square means test.

2.5.2. Acidification

Replacing essential plant nutrients, which are no longer available because of SOM depletion, by applying NH_4-based fertilizers, can degrade soil by increasing acidity during hydrolysis that releases H ions [47]. Chen *et al.* [48] showed that N sources have different effects on soil acidity and ranked common fertilizer materials in the order $(NH_4)_2SO_4$ > NH_4Cl > NH_4NO_3 > anhydrous NH_3 > urea. Soil degradation through increasing acidity depresses the efficacy of subsequent fertilizer applications for sustaining crop yields [49], thereby resulting in inefficient use of fertilizers [43]. The long-term, 30 years, application of N fertilizer progressively reduced the 0–7.5 cm soil pH as cropping sequence intensified from WF to CW from an initial pH of 6.5 to 5.5 in CT-WF and 5.0 in NT-CW and CT-CW for dryland production in the northern Great Plains (Table 2). Likewise, tillage indirectly affects soil acidity as a result of enhanced soil water conservation using NT compared with CT that increases crop yields, the amount of required N fertilizer, and the removal of basic cations in harvested grain and biomass [43,50]. Soil acidification as a consequence of increased fertilization to intensify cropping systems productivity, as noted for the northern Great Plains, may exemplify an acceptable self-perpetuating production risk that requires additional neutralizing amendments as precipitation increases to the east. In contrast, this acidification provides a benefit for calcareous soils common to western North America.

Table 2. Effect of 30 years of no tillage (NT) and conventional tillage (CT) residue management with either continuous spring wheat (CW) or wheat-fallow (WF) cropping sequences on soil pH and bulk density at various soil depths for a field site 10 km north of Culbertson, MT.

Tillage and Cropping sequence	pH at the soil depth					
	0–7.5 cm	7.5–15 cm	15–30 cm	30–60 cm	60–90 cm	90–120 cm
NT-CW	5.33 ab †	6.50 ab	7.60 a	8.35 a	8.58 a	8.75 a
CT-CW	5.05 b	6.15 b	7.58 a	8.25 b	8.63 a	8.70 a
CT-WF	5.73 a	7.03 a	7.65 a	8.25 a	8.50 a	8.66 a
	Bulk density (Mg m^{-3}) at the soil depth					
	0–7.5 cm	7.5–15 cm	15–30 cm	30–60 cm	60–90 cm	90–120 cm
NT-CW	1.15 b †	1.48 a	1.49 a	1.67 a	1.52 a	1.64 a
CT-CW	1.26 b	1.38 a	1.43 a	1.55 a	1.51 a	1.68 a
CT-WF	1.45 a	1.48 a	1.53a	1.62 a	1.60 a	1.70 a

† Common parameter values within columns followed by the same letters are not significantly different at $P = 0.05$ according to the least square means test.

2.5.3. Salinization

Accumulating salts, including sodium, represents another problematic type of chemical soil degradation in North America that affects agronomic production, albeit limited to ~1% of the total land area [51]. A combination of geological, climatic, and cultural practices including cropping systems affect the development of saline seeps in some 800,000 ha of non-irrigated land in the northern Great Plains [52]. Seeps form when precipitation not used by plants moves below the root zone through the salt-laden substrata to impermeable layers and eventually flows from the recharge area to depressions where water evaporates leaving salt deposits enriched in Na, Ca, Mg, SO_4-S, and NO_3-N that retard crop growth [53]. In Canada, diversion of surface drainage from recharge areas and intensifying cropping systems to consume precipitation are recommended for mitigating management practice dependent "secondary salinity" problems [54]. Secondary salinity resulting from irrigation to supply part of the crop water use permitted intensification of cropping systems on arid and semi-arid land. This intensified production on ~7.5% of US farm land produced 55% of domestic crop value [55], but Postel [56] noted that salinity affected ~23% of that irrigated land. Where sufficient salt is applied to reduce crop yield, irrigation may be a "Faustian Bargain" degrading soil and requiring corrective management intervention, such as leaching or alternate crop selection.

3. Mitigation Strategies for Reversing Soil Degradation

The number of site-specific management strategies to mitigate degraded or degrading soil is diverse, but when considered from a broad perspective on potential solutions converge to a limited paradigm. Physical and chemical soil degradation through erosion, compaction, and acidification are commonly connected by absent biomass cover and declining soil organic matter as a result of tillage or moderated crop production. That is, residue preservation with reduced or no tillage is an avenue to increase soil organic matter while protecting soil from the erosion processes and mitigating soil compaction. Intensified cropping systems, likewise, increase biomass for greater soil organic matter to stabilize aggregates and render the soil less susceptible to erosion. The common management perspective for improving soil health, quality, and productivity is to reverse soil degradation by using residue retaining tillage practices and, where possible, intensifying cropping systems within rotations or by added cover crops.

Tillage and soil compaction also express a wide variety of site-specific interactions where more intensive cropping sequences offset tillage related compaction. For example, even though soil compaction generally increases as the frequency of conventional tillage increases, data from the Central Great Plains has shown that even in the absence of soil disturbing tillage (*i.e.*, no-tillage) compaction can increase as a result of soil consolidation during routine farm operations [53]. Another study in eastern Montana, comparing CT and NT after 30 year under dryland continuous wheat (CW) or wheat fallow (WF) cropping sequences showed that soil bulk density within the 0 to 7.5 cm depth increment was not different between NT-CW and CT-CW (Table 2). However, the bulk density was 13% to 21% greater for the same depth increment in CT-WF (1.45 Mg m^{-3}) than NT-CW and CT-CW (1.15 to 1.26 Mg m^{-3}). One reason suggested for this response was reduced root growth and lower soil organic C input (Figure 2).

3.1. Tillage Management

Moldboard plowing, which was the dominant tillage system for many years, buries essentially all plant residues beneath the soil surface. Conservation tillage was defined in 1984 by the USDA Soil Conservation Service (currently Natural Resources Conservation Service) as "any tillage system that maintains at least 30% of the soil surface cover by residue after planting primarily where the objective is to reduce water erosion". When wind erosion is a concern, the term refers to tillage systems that maintain at least 1000 pounds per acre (1120 kg ha^{-1}) of "flat small-grain residue equivalents" on the soil surface during critical erosion periods [57]. The significance of focusing on 30% cover originated from studies showing that this amount would reduce erosion by at least 50% compared to bare, fallow soil [58].

Compared with conventional tillage, both no tillage and conservation tillage limit soil disturbance and retain crop residue. The decreased tillage intensity subsequently increases SOM as aeration and mineralization are reduced [27]. This residue-retaining conservation tillage in the southern Great Plains practices also form mulches that reduce evaporation, increase soil water that, consequently, engendered greater crop yields [59] and related biomass to enhance SOC. The resulting greater soil organic matter promotes soil aggregation by enhancing the growth of fungi and hyphae that binds the particles together [27,28,60]. The larger stabilized surface aggregates limit soil susceptibility to wind erosion and improve rain infiltration for reduced runoff and, consequently, soil entrainment in eroding water [61].

To mitigate wind and water erosion, the types of tillage that can generally meet the goal of leaving enough crop residue on the soil surface after planting are no-till, ridge-till, and mulch-till [62]. The Conservation Technology Information Center (CTIC) classifies tillage methods that leave from 15% to 30% cover after planting as reduced tillage, and systems that leave from 0% to 15% as conventional tillage [62]. Based on that CTIC National Crop Management Survey of the USA data presented in Figure 4, tillage intensity has reduced steadily and significantly since 1990. That is, no-till has increased from less than 6% in 1990 to almost 24% in 2008, and when mulch-till and ridge-till amounts are included, tillage systems that meet the definition of conservation tillage have increased from about 26% to 42% during that 18-year period. Data are not readily available prior to 1990, but there was little or no widespread emphasis on reducing tillage intensity before the 1990s.

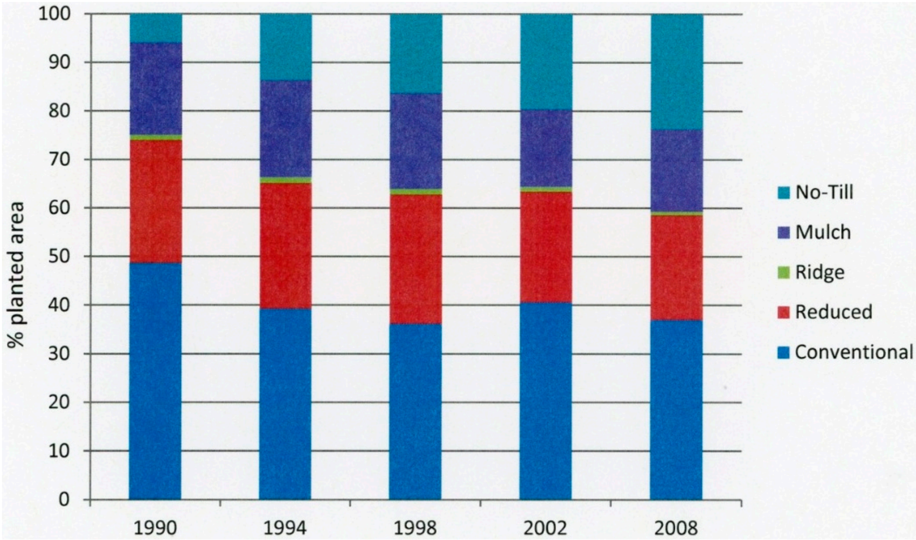

Figure 4. Types of tillage for planted area in the U.S., 1990 to 2008; no-till, mulch, and ridge tillage increased from 26% to 42% while providing >30% residue cover; reduced till 15% to 30% remained near a static 20%–25% of planted area, and conventional till, providing 0% to 15% residue cover on soil surface following planting, declined from ~48% to 37% of the planted area [62].

Beginning in 1982, there was significant effort to reduce soil erosion on all cropland [63]. From 1982 to 1997, sheet and rill erosion were reduced by 41% while wind erosion decreased by 43% (Figure 5) [64]. Since then, there continues to be a clear connection between tillage intensity and soil erosion even though both the reduction in tillage intensity and the reduction in soil erosion have declined. Ideally, no-tillage systems are best for mitigating soil degradation because they maximize the amount of crop residue remaining on the soil surface. Furthermore, in addition to reducing erosion, the residues reduce evaporation of water from the soil surface, which is particularly important in dry areas and during periods of drought. However, there are some disadvantages with no-till systems, such as increased dependence on herbicides and slow soil warming on poorly drained soils that have prevented adoption by many producers. Also, despite the numerically lower erodible fraction for soil managed with conservation tillage compared with CT, Van Pelt *et al.* [65] concluded that the protective mantle of crop residue is crucial to preventing erosion in the North American Central Great Plains. Conservation tillage also reduces soil compaction by increasing root growth and SOC [66], soil erosion by increasing surface residue cover [67], fuel costs for tillage, and potential global warming by increasing soil C sequestration [68] by conserving more soil water and increasing crop yields [29,44,47]. Although successful conservation tillage may require higher N fertilization because of enhanced N immobilization due to increased surface residue accumulation [69], benefits for mitigating soil degradation by increasing SOC and reducing soil compaction and erosion outweigh limitations. As a result, the conservation or no-tillage paradigm is recommended to improve soil and environmental quality and sustain crop yields.

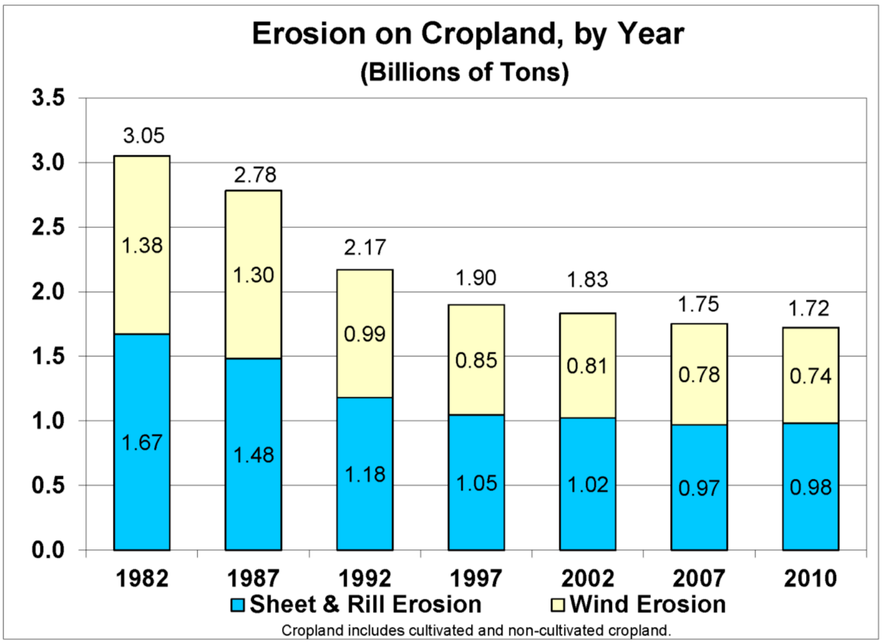

Figure 5. Combined mean water and wind erosion on U.S. cropland from 1982 until 2010 [64].

A similar, but somewhat more encouraging picture has emerged for Canada. Data presented in Figure 6 show that no-till increased from 7% in 1991 to 56% in 2011 while conventional tillage decreased from 68% in 1991 to 19% in 2011 [70]. Conservation tillage, defined in their analysis as having tillage intensity between no-till and conventional till, remained between about 25% and 30%. Similar to the U.S. where adoption of no-till increased from 6% in 1990 to 24% in 2008, adoption in Canada increased from 7% in 1991 to 56% in 2011. Overlapping within the 1991 to 2011 period of increasing no-till management, there was also a significant decrease in soil erosion risk in Canada from 1981 to 2006 associated with the decrease in tillage intensity (Figure 7). In contrast to the rate of soil erosion in the U.S. that has declined since 1997, the greater rate of reduction in soil erosion for Canada appears to be associated with both the increase in no-till area that reduces tillage intensity and the conversion of erodible land from annual crops to perennial forages and pastures [71].

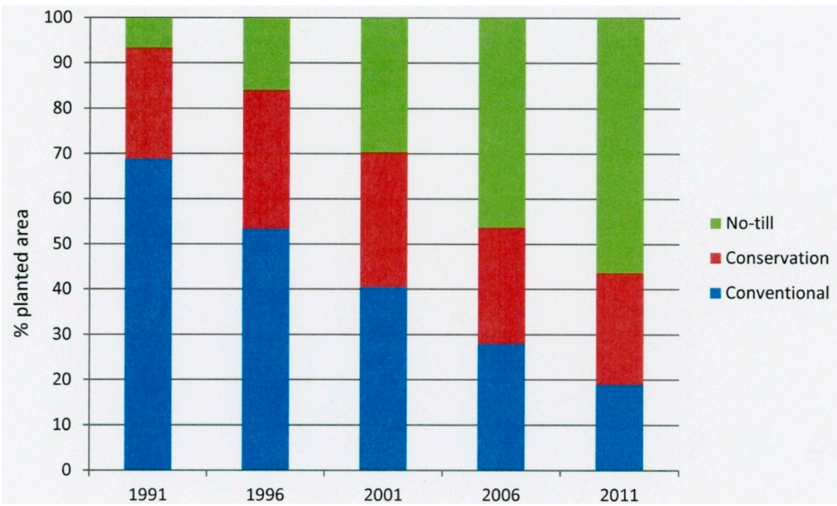

Figure 6. Types of tillage for planted area in Canada, 1991 to 2011; conservation tillage had tillage intensity between no-till and conventional tillage [70].

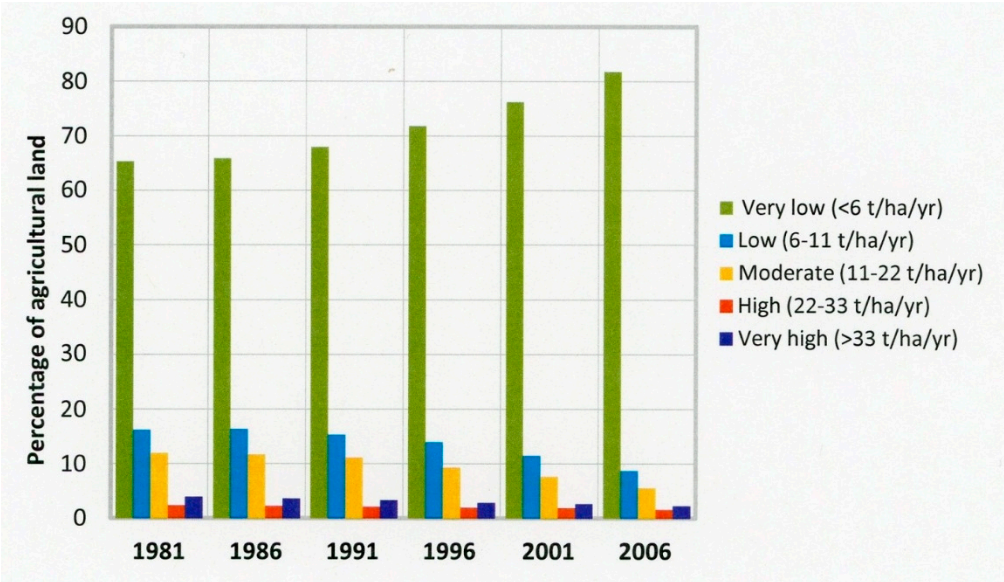

Figure 7. Soil erosion risk for cropland in Canada, 1981 to 2006 [71].

3.2. Cover Crops and Carbon Sequestration

Cover crops are defined as plant biomass grown for the purpose of providing a protective cover to prevent soil erosion and to limit nutrient loss by leaching or in runoff [72]. To this definition, Delgado *et al.* [73] added other management goals, including water conservation, nutrient scavenging and cycling management, and short duration livestock grazing. Grasses, legumes, and forbs grown for seasonal cover and conservation are not considered a production "crop". Cover crops in humid and subhumid regions of North America, and especially in areas with moderate winter conditions, such as the southeastern USA [74], are usually planted in the fall after summer cash crops are harvested. In semiarid regions with limited precipitation or regions with a short growing season, such as in the northern Great Plains, there are fewer opportunities for these crops. For cotton (*Gossypium hirsutum* L.) monocultures on the Texas High Plains that generally produce limited residue, Keeling *et al.* [75] introduced a chemically terminated wheat cover crop to control wind erosion. This practice increased mean irrigated cotton lint yield compared with conventional tillage, but establishment of the dryland cotton cash crop or wheat cover crop was problematic despite improved rain infiltration and greater crop water use [76]. Water is the most limiting factor in the central and southern Great Plains, so although growth of fall-planted cover crops may suffer due to low soil water availability, the real problem is that any use of soil water and N by cover crops may reduce cash crop yields compared with leaving the soil in a fallow condition [77,78]. Nevertheless, cover crops increase soil aggregation, water infiltration and water holding capacity [79], reduce soil erosion [80], and increase root growth of summer crops [32] over no cover crop.

Cover crops help mitigate soil degradation by improving nutrient management either by providing a nutrient source or by scavenging nutrients for eventual release from decomposing plant residues and recycling them to subsequent crops. The use of legume cover crops can supply N through fixation to increase crop yields compared with nonlegumes or no cover crop [30]. In contrast, nonlegume cover crops scavenge the soil for residual N following harvest of the primary crop, thereby reducing soil profile NO_3-N content and the potential for N leaching [81]. For example, a rye (*Secale cereale* L.) cover crop was projected to reduce NO_3 losses in drainage water within the Corn Belt states from a measured 11% [82] to a modeled 42.5% [83]. This could retain the N on site for use by subsequent crops and may have collateral benefits of reducing nutrient contamination that is one cause of hypoxia in the Gulf of Mexico. Growing a mixture of legume and nonlegume cover crops can maintain or increase SOC and SON concentrations by providing additional crop residue, which increases C and N inputs to the soil [22,37]. It can also help reduce N fertilizer requirements for subsequent summer crops [22,80].

In addition to providing protection against soil erosion and improving nutrient cycling, the use of cover crops and better management of crop residues have also been suggested as practices for enhancing carbon sequestration. The current focus on sequestering C in soils is to reduce CO_2 concentrations in the atmosphere and improve soil quality. Lal *et al.* [84] estimated that from 35 to 107 million Mg C could potentially be sequestered annually by conservation tillage and residue management on U.S. cropland. Although this might be possible, it is likely not feasible because sequestering 100 million Mg C would also sequester approximately 8 million Mg N and 2 million Mg P, which is about 75% and 100% of the amounts of these elements added each year in the U.S. through chemical fertilizers. Therefore, while efforts should continue to sequester C in soils, it is clear that the technology, practices, and policies needed to realize the estimated potential will be difficult to implement and the first priority should be to prevent further loss of SOC.

3.3. Intensified Cropping Systems

Traditionally, intensified farm production relied on established practices such as conventional tillage with monocropping and high rates of N fertilization to increase crop biomass yields. However, cropping systems in semi-arid regions of North America can be intensified by reducing the fallow frequency within crop sequences, such as by converting wheat-fallow (WF) to annually cropped wheat (Figure 8) or by introducing more productive summer crops into the rotation [85]. One example of the latter approach is the wheat-sorghum-fallow (WSF) rotation shown in Figure 9 [85]. Similar data from Saskatchewan showed that using fertilizer and crop sequences with progressively less frequent fallow periods increased annualized wheat grain and biomass yields that subsequently increased SOC [86]. Hansen *et al.* [87] also noted that cropping system intensification produced progressively greater biomass and SOC and, consequently, improved physical properties. Within the described W-F and WSF rotations a possibility exists for spring-planted cover crops to grow during early summer and partially replace fallow provided that normal cash crop production is unaffected by the redirected precipitation, especially in the semi-arid Great Plains. Where summer cover crops are grown in water conserving NT systems, aboveground biomass may be used for hay to improve cover crop economics [29,44,47]. The added biomass of intensified cropping systems that increases SOC and provides a protective cover can also decrease soil degradation by erosion. The benefits of residue to reduce soil entrainment by slowing wind or intercepting rain drop impact that leads to greater runoff combines with SOC stabilized aggregation to reduce soil erodibility [88,89].

In addition to increasing biomass for SOC and residue for soil protection, intensified cropping systems provide drainage and nutrient management alternatives in more humid North American climates. The cropping system intensification paradigm exemplifies a means to improved soil and environmental quality that also sustains crop yields.

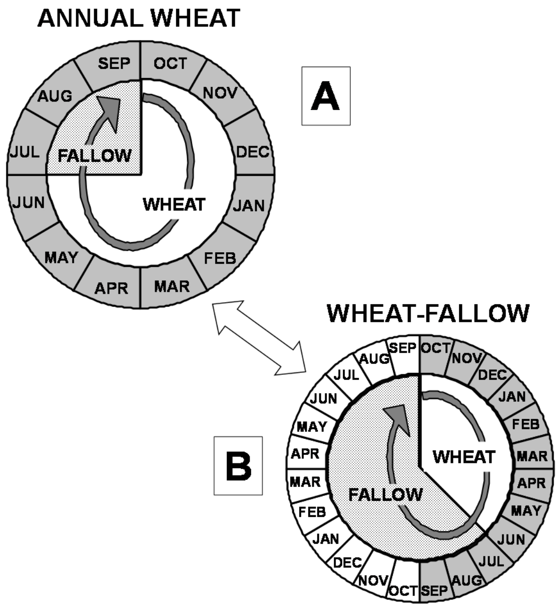

Figure 8. The annual wheat (**A**) and wheat-fallow (**B**) cropping sequences diagramed as a one or two year cycle, beginning with wheat establishment in October for the southern Great Plains [85]. In both sequences, wheat is harvested about nine months after planting and either fallowed briefly during July–September or after an additional 12 months if precipitation was insufficient for wheat establishment and growth.

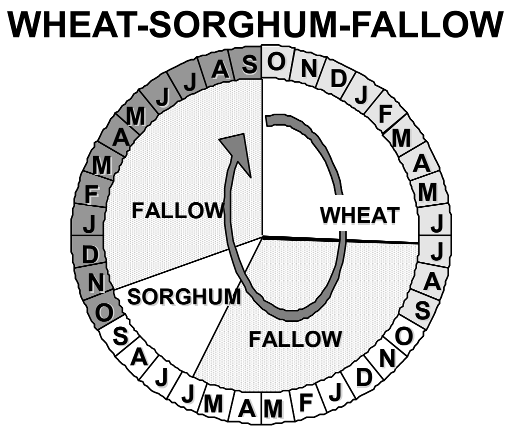

Figure 9. The wheat-sorghum-fallow (WSF) rotation diagramed as a three-year cycle beginning with wheat establishment in October and subsequent harvest 10-months later in July [85]. After delaying until June of the second year, grain sorghum is grown using stored soil water to augment summer rainfall. The soil is fallowed after sorghum harvest in November of the uncropped third year when the cycle repeats with wheat planting.

Animal grazing can also be used to intensify farm production. Doing so can provide weed control, reduce feed cost, increase soil organic matter, and redistribute nutrients without depressing crop yields [49,90,91]. In the southeastern USA, moderate animal grazing can improve soil quality and productivity by enhancing soil organic matter and nutrient cycling, but excessive grazing can degrade soil properties by reducing SOM [92]. In the southern Great Plains, Baumhardt *et al.* [93] reported that surface compaction due to grazing cattle on vegetative dual purpose wheat without remediating tillage increased the soil profile penetration resistance. They also observed reduced water conservation resulting in depressed crop yields after three years compared with ungrazed no-tillage cropping systems production.

Excessive tillage and grazing used to intensify agricultural production can degrade soil by deforming or destroying soil structure [94]. This ultimately leads to compaction and a decrease in void space that, by definition, increases bulk density [95]. For example, in northwest Ohio, soil compaction was shown to reduce water movement, infiltration capacity, and root growth that, in turn, limited crop yield [96].

3.4. Engineering Strategies

For water erosion control, much of the early effort focused on using contour terraces. Although this worked well in many cases, there were major disadvantages because the terraces would frequently break during high intensity precipitation events. Also, as machinery became larger, contour terraces did not work well because space between terraces was highly variable. Parallel terraces were sometimes used to eliminate this problem, but this required more soil movement, made them more expensive to build, and often created soil fertility problems. Based on these experiences we maintain that long-term efforts to restore soil carbon by decreasing tillage intensities and retaining an appropriate amount of crop residue will be the most efficient approach for restoring degraded soils in North America.

4. Concluding Remarks

The U.S. Census Bureau [97] reported that the global population doubled from three billion in 1959 to six billion by 1999 and projected continued population growth to reach nine billion by 2044, which will require a corresponding increase in agricultural production to insure food security. Some 200 years after Thomas Malthus postulated failing global food security, Postel [98] observed in 1998 that water required for expanding overall crop production may be unavailable for degraded soils; thus, further threatening food security. In contrast, a 2013 report by Ausubel *et al.* [99] shows that the arable land required for sustaining crop production decreased by 65% during the period from 1961 to 2009, or the same period when the corresponding global population practically doubled. These very contradictory interpretations of resource productivity highlight unsettled future food security concerns, in part, because developing technologies have historically amplified agricultural production from fixed land resources to secure food demand. Soil degradation as a consequence of unsustainable management, however, may gradually decrease land productivity through *in-situ* soil salinization, compaction, declining SOM, and deteriorating aggregate stability.

In the concluding chapter of a soil degradation review, Lal and Stewart [100] advanced the case for separating “emotional rhetoric” of soil degradation from “precise scientific” results assessing soil resource condition and management. Principal agents that degrade soil, such as erosion or compaction frequently, follow the application of unsuitable agricultural management practices, including soil-inverting tillage. Eventually, scientific investigation advances improved management practices that reverse or mitigate soil degradation by negating the effects of causal processes or agents. Not surprisingly, soil erosion is mitigated through the use of cover crops and residue retaining tillage practices to promote aggregate stabilizing organic matter that, in turn, reduces soil susceptibility to erosion while providing crop mulches to intercept raindrop impact and prevent soil entrainment by wind or water. Improved soil and crop management practices must integrate unique differences in climate and soil specific properties, which deny the application of a common solution or priority for mitigating soil degradation. Preventing soil degradation, however, must control the universal processes or agents governing erosion, contamination, destabilization, and nutrient or SOM losses by crop production paradigms that emphasize resource stewardship.

Acknowledgments

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Author Contributions

All authors contributed equally to preparation of various components that were combined in this paper.

Conflicts of Interest

The authors declare no conflict of interest.

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