Chapter 14
Enhancing Soil Aggregation in No-Till Farming Systems

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Abstract Improving soil physical properties, such as aggregate stability, is essential to reducing soil erodibility, stabilizing C and nutrients, improving water, air, and heat fluxes, and supporting root growth. No-till (NT) farming generally improves soil aggregate stability near the soil surface, but the extent of this improvement can depend on the companion practices used with NT, including crop residues, cover crops, crop rotations, organic amendments (i.e., manure, biochar), inorganic fertilization, or one-time or strategic tillage. The objective of this paper is to discuss how companion practices to NT affect soil aggregate stability (a sensitive indicator of changes in soil structure), as compared to NT without such companion practices. Research indicates that companion practices can differently affect aggregate stability in NT soils relative to NT without companion practices. For example, inorganic fertilization does not affect aggregate stability in 70% of cases, but animal manure can increase aggregate stability in 60% of cases. Crop residue baling at high rates can reduce near-surface aggregate stability by 7–64%, particularly in the long term (> 3 years). This reduction can be especially large at low rates of inorganic fertilization. Practices such as strategic tillage and moderate crop residue grazing (<30% residue removal) do not generally affect aggregate stability. Conversely, cover crops, animal manure, biochar, and intensified crop rotations can increase the ability of NT soils to improve aggregate stability in the long term (> 5 years), particularly in low organic matter (<2.5%). While the latter practices offer much promise to enhance aggregate stability, challenges associated with cover crop management, biochar production, and others should be addressed. *In sum, adding* cover crops, animal manure, biochar, and using intensified crop rotations can enhance the potential of no-till to further enhance soil aggregation, especially when such practices are targeted to low organic matter, eroded or degraded NT soils.

Keywords No-till · Soil structure · Soil aggregate stability · Cover crops · Inorganic fertilization · Crop residue removal · Crop residue grazing · Crop rotations · Biochar · Animal manure

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14.1 Introduction

Maintaining or improving soil aggregation is critical to reduce water and wind erosion, filter runoff, retain and recycle nutrients and water, protect and sequester organic C, mediate soil microbial processes, and support root development and crop production. For example, the stability, size, and distribution of soil aggregates determine the volume of pore space for the movement of water, air, and heat. Large pores favor rapid movement of water, air, and heat, while small pores are important to retention of available soil water and protection of C and nutrients. An increase in organic matter, root biomass, and biological activity promotes soil aggregation (Blanco-Canqui and Lal 2004; Rosenzweig et al. 2018).

No-till farming generally increases surface soil aggregate stability relative to tilled soils, but the extent of such increase can vary. A review by Blanco-Canqui and Ruis (2018) concluded that NT-induced increase in near-surface wet soil aggregate stability ranged from 1 to 97% compared with tilled soils. This high variability in NT effects can be partly attributed to the differences in companion practices used with NT but also to initial soil properties such as soil organic matter content (Fig. 14.1). The magnitude to which each companion practice changes aggregate stability in NT soils is, however, unclear. For example, strategic tillage, the one-time or strategic tillage of long-term NT soils, is used in some cases to manage herbicide-resistant weeds, excessive soil compaction, C and nutrient stratification, and other challenges with continuous NT farming, but its impact on aggregate stability is not widely discussed. Thus, the objective of this paper is to discuss how companion practices to NT affect soil aggregate stability as compared to NT without such companion practices. This paper focuses on wet aggregate stability, hereafter referred to as aggregate stability, as the most sensitive indicator of changes in soil structure.

14.2 Does Inorganic Fertilization Increase Aggregate Stability?

Inorganic fertilization is a common companion practice in NT systems for supplying nutrients, which leads to the question: How does inorganic fertilizer affect soil aggregate stability? The summary of research findings in Table 14.1 indicates that

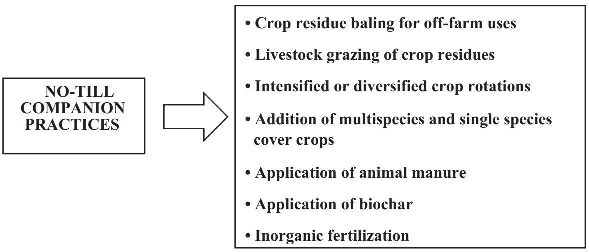

Fig. 14.1 Depending on farmer's preferences, accessibility, needs, and goals, a number of practices are used as companion to no-till farming

Table 14.1 Impacts of inorganic fertilization on soil aggregate stability indexes in no-till (NT) systems

Location	Soil	Crop	Years in NT	Fertilization rate per year	Fertilization impact on aggregate stability	References
Nebraska, USA	Silty clay loam	Corn	28	0, 80, and 160 kg N ha^{-1}	Increased MWD by 43% in the upper 0.075 m depth	Blanco-Canqui et al. (2014a)
					Reduced MWD by 47% in the 0.15–0.6 m depth	
Kansas, USA	Silt loam	Grain sorghum	26	0 and 135 kg N ha^{-1}	Increased MWD by about 24% in the upper 0.15 m depth	Presley et al. (2012)
Kansas, USA	Silt loam	Corn	50	0, 45, 90, 134, 179, and 224 kg N ha^{-1}; 20 and 40 kg P ha^{-1}	No effect in the upper 0.075 m depth	Blanco-Canqui and Schlegel (2013)
					Reduced MWD by 30–160% in the 0.075–0.3 m depth at high N and P rates	
Mississippi, USA	Silt loam	Cotton	3	0 and 112 N $kg^{-}ha^{-1}$	No effect on WAS	Adeli et al. (2019)
South Africa	Clay loam	Corn	13	0, 100, and 200 kg^{-1} N ha^{-1}	No effect on MWD	Sithole et al. (2019)
Argentina	Loam	Corn-soybean-wheat	7	0, 120, and 150 kg N ha^{-1}; 30 kg P ha^{-1}	No effect on MWD	Wyngaard et al. (2012)

MWD Mean weight diameter of water-stable aggregates, *WAS* Water-stable aggregates

the use of N and P fertilizers does not alter aggregate stability in most NT soils (70% of cases). Table 14.1 also indicates that, in a few cases, N and P fertilization can either increase aggregate stability by 24–43% or reduce it by 30–160%. The reduction appears to occur in the 0–075-0.30 m depth. The increased aggregate stability with fertilization can be due to increased biomass production and biomass C input, whereas the reduced aggregate stability can be due to a fertilization-induced release of NH_4^+ and decrease in soil pH (Haynes and Naidu, 1998). An increase in NH_4^+ in the soil solution can disperse soil colloids and deflocculate aggregates. Also, Blanco-Canqui and Schlegel (2013) found that the decrease in aggregate stability was larger when both N and P fertilizers were applied at >100 kg N ha^{-1} year^{-1} and > 40 kg P ha^{-1} year^{-1} than when N or P was applied alone or when both were applied at lower rates. Overall, inorganic fertilization does not increase aggregate stability in most cases in spite of increased crop biomass production with fertilization. This finding appears to corroborate that the main value of adding inorganic fertilizers to crops is to increase crop yields and not to improve soil properties such as aggregate stability.

14.3 Does Animal Manure Application Increase Aggregate Stability?

The summary in Table 14.2 indicates that, in about 60% of cases, animal manure application to NT fields increases surface soil aggregate stability by 8–75% relative to NT systems without manure. It is well recognized that manure application can improve soil aggregation by increasing soil organic C concentration, microbial biomass and activity, and plant growth, and inducing slight hydrophobic properties to soil. The manure-induced slight water repellency reduces aggregate slaking. Manure also contains organic matter at different stages of decomposition, which can differently impact soil aggregation. Manure-derived particulate organic matter promotes aggregation in the short term, whereas, in the long term, manure transformation into mineral-associated organic matter can promote formation of stable microaggregates (Aoyama et al. 1999). In some cases, animal manure may have a high concentration of monovalents (Na^+, NH_4^+, and K^+), which can cause dispersion of colloids, thereby reducing soil aggregation (Whalen and Chang 2002).

Table 14.2 also suggests the following trends. First, composted manure can increase aggregate stability more than raw manure as the former provides decomposed organic materials and encourages biological activity to bind soil particles and form aggregates (Jiao et al. (2006)). Second, large amounts of manure may be needed to significantly increase aggregate stability. Jiao et al. (2006) applied beef manure at 0, 15, 30, and 45 Mg ha^{-1} year^{-1} and found that only 30 and 45 Mg ha^{-1} year^{-1} increased aggregate stability, suggesting that only high rates

Table 14.2 Impacts of animal manure application on aggregate stability indexes in no-till (NT) soils

Location	Soil texture	Crop	Years of manure application	Manure type	Manure rate (Mg ha^{-1} year^{-1})	Soil depth (m)	Manure effect on aggregate stability	References
Ohio, USA	Silt loam	Corn	41	Beef	15	0.10	Increased kinetic energy of raindrops needed to break aggregates by 39%	Blanco-Canqui et al. (2007)
Canada	Sandy loam	Corn and corn-soybean	4	Composted beef manure	0, 15, 30, and 45	0.10	30 and 40 Mg/ha of manure increased WSA (> 2 mm) by about 25%	Jiao et al. (2006)
Mississippi, USA	Silt loam	Cotton	3	Poultry litter	6.7	0.15	Increased WAS by 8%	Adeli et al. (2019)
Nebraska, USA	Site 1 (two silt loams)	Corn	30 days	Manure	50	0.025	Manure increased aggregate size (> 2 mm) by 67%	Wortmann and Shapiro (2008)
				Composted manure			Composted manure increased aggregate size (> 2 mm) by 75%	
	Site 2 (silt loam and loam)	Not available	4	Beef feedlot and swine slurry manure	46 (beef manure) for silt loam		Beef feedlot had no effect	
					2.7 (swine manure) for loam		Swine slurry increased aggregate size (> 0.25 mm) by 21%	
	Site 3 (silt loam)	Corn-soybean	4	Composted beef manure with low and high P	66.7 low P		No effect	
					66.7 high P			
Nebraska, USA	Silt loam	Corn	3	Sheep and beef	17.3 (sheep manure in year 1)	0–0.025	No effect on MWD	Blanco-Canqui et al. (2014b)
					19 (beef manure in year 2)			

MWD Mean weight diameter of water-stable aggregates, *WAS* Water-stable aggregates

(>15 Mg ha^{-1} $year^{-1}$) of manure application can induce changes in aggregate stability. In general, animal manure application generally increases aggregate stability.

14.4 Does Baling Crop Residues Reduce Aggregate Stability?

Crop residues from NT fields are often baled, particularly in the US Midwest such as for livestock feeding and biofuel production. Thus, the question is: How does baling crop residues affect aggregate stability? Table 14.3 indicates that corn residue removal commonly reduces aggregate stability by 12–64%. Several findings emerge from Table 14.3 as follows:

- In corn producing systems of the US Midwest, > 5.5 Mg ha^{-1} $year^{-1}$ of crop residues should be retained to maintain aggregate stability with greater retention for highly erodible soils (Wortmann et al. 2012; Johnson et al. 2014).
- Corn residue removal reduces aggregate stability more at low than at high rates of N fertilizer application, although few studies have assessed the interactions of different levels of residue removal and N fertilization. High rates of N application appear to offset the adverse effects of residue removal on aggregate stability. This is possibly due to the greater residue production and C input under high N rates.
- Continuous crop residue removal for >3 years is more detrimental to aggregate stability than short-term or infrequent removal.
- Decrease in aggregate stability due to crop residue removal is often confined to the upper 0.05 or 0.10 m of the soil surface especially in the short term (<3 years). Continued residue removal in the long term can, however, reduce aggregate stability at deeper depths (Stewart et al. 2019).

No-till performance is a function of crop residue retained in the field (Table 14.3). Residues protect the soil from raindrops and other erosive forces, stabilize soil, reduce aggregate detachment, increase soil organic C concentration, and provide C and energy sources to soil microorganisms (Johnson et al. 2014). Low residue retention also rapidly alters surface soil water content and soil temperature, inducing abrupt fluctuations in drying-wetting, freezing-thawing, and swelling-shrinking cycles, particularly in winter and spring. These abrupt cycles degrade the inter- and intra-aggregate bonds (Blanco-Canqui et al. 2016). For example, intra-aggregate pores expand during freezing, increasing the total aggregate volume. In contrast, rapid drying of the soil decreases aggregate size and reduces intra-aggregate macroporosity. In summary, leaving sufficient crop residue retention in NT fields is important to maintain or improve aggregate stability because NT fields with limited or no residues can be equally or more prone to degradation than tilled fields.

Table 14.3 Impacts of corn residue removal on soil aggregate stability in no-till (NT) systems

Location	Crop	Soil	Years after residue removal	Amount of residue removal (Mg ha^{-1})	Amount of residue left (Mg ha^{-1})	Removal rate (%)	Soil depth (m)	Residue removal effect on aggregate stability	References
Nebraska, USA	Irrigated continuous corn	Silt loam	6	5.6	4.4	56	0–0.05	Reduced MWD by 23%	Sindelar et al. (2019)
Kansas, USA	Irrigated continuous corn	Silt loam	3	1.67	5.00	25	0–0.05	No effect on MWD	Kenney et al. (2015)
				3.45	3.47	50			
				5.03	1.68	75			
				6.24	0	100			
	Irrigated continuous corn	Loam	3	1.80	5.41	25		No effect on MWD	
				3.58	3.59	50			
				5.22	1.74	75			
				6.45	0	100			
	Rainfed continuous corn	Loam	3	0.85	2.53	25		No effect on MWD	
				1.57	1.59	50			
				2.37	0.79	75			
				4.33	0	100		Reduced MWD by 64%	
Nebraska, USA	Irrigated continuous corn	Sandy loam	3	8.14	3.32	71	0–0.05	No effect on MWD	Blanco-Canqui et al. (2017)
Nebraska, USA	Rainfed continuous corn	Silt loam	12	2.7 to 3.3	2.21 to 1.6	55	0–0.05	Reduced WSA (>0.5 mm) by about 23% at 60 kg N ha^{-1} $year^{-1}$	Jin et al. (2015)
								No effect at 120 and 180 kg N ha^{-1} $year^{-1}$	

(continued)

Table 14.3 (continued)

Location	Crop	Soil	Years after residue removal	Amount of residue removal (Mg ha^{-1})	Amount of residue left (Mg ha^{-1})	Removal rate (%)	Soil depth (m)	Residue removal effect on aggregate stability	References
Minnesota, USA	Rainfed continuous corn	Silt loam	12	NA	NA	90	0–0.05	Reduced amount of macroaggregates (>0.25 mm) by 59%	Laird and Chang (2013)
Nebraska, USA (3 sites)	Irrigated continuous corn	Silt loam	3	5.4	4.2	56	0–0.05	No effect on MWD	Rakkar et al. (2019)
Nebraska, USA	Irrigated continuous corn	Silt loam	3	9.7	5.0	64	0–0.05	Reduced MWD by 64%	Ruis et al. (2018)
Illinois, USA (4 sites)	Rainfed continuous corn	Silt loams	8	3.4	4.2	45	0–0.15	Both removal rates reduced WSA by about 9% at 134 kg N ha^{-1} year^{-1}	Villamil et al. (2015)
				6.8	0.8	89		No effect of removal on WSA at 268 kg N ha^{-1} year^{-1}	

MWD Mean weight diameter of water-stable aggregates, *WAS* Water-stable aggregates

14.5 Does Grazing Crop Residues Reduce Aggregate Stability?

Livestock grazing of crop residues is a common component of synergistic crop-livestock integration. This leads to the question: How does grazing of crop residues affect aggregate stability? While research data are relatively few, a review found that moderate grazing of crop residues has small and mixed effects on aggregate stability (Rakkar and Blanco-Canqui 2018). Moderate crop residue grazing often removes <30% of residues and has much smaller effects on aggregate stability than high rates of residue baling. The reasons for the small or no effects of crop residue grazing effects on aggregate stability deserve further discussion. On one hand, residue grazing may reduce aggregate stability by (1) reducing organic material return to the soil, (2) exposing the soil surface to erosive forces such as raindrops, and (3) inducing abrupt fluctuations in wet-dry and freeze-thaw cycles (Layton et al. 1993). On the other hand, grazing livestock adds manure to grazed fields. Manure input may not only offset the potential adverse effects of residue grazing but may also improve aggregate stability (Rakkar and Blanco-Canqui 2018). Additionally, hoof action during grazing can compress soil aggregates and potentially increase soil aggregate strength or stability relative to non-grazed soils. Overall, moderate grazing of crop residues in NT cropping systems has small or no effects on aggregate stability and can be valuable to crop-livestock integration.

14.6 How Do Cropping Systems Affect Aggregate Stability?

The cropping system effects on soil aggregation depend on the amount of residue produced and returned to the soil. High-biomass producing crops in the rotation can improve aggregate stability over rotations with low biomass production. High-biomass producing crops such as continuous corn increases aggregate stability over low-biomass producing crops such as corn-soybean rotation, continuous soybean, and continuous tobacco (Table 14.4) (Zuber et al. 2015).

In water limited environments, such as in the semiarid US Great Plains, reducing the frequency of one-year fallow periods can improve aggregate stability (Table 14.4). Note that fallow in this paper refers to fallowing where all vegetative growth is prevented by using chemicals to store water. No-till with fallow periods every 3 or 4 year generally increases aggregate stability relative to fallow periods every other year. As the frequency of fallow periods decreases, mean annual biomass input can increase. One strategy to reduce fallow periods in crop-fallow systems is by growing grain, forage or cover crops that are terminated early enough for some water accumulation before sowing of the primary crop. The precipitation pattern is important to such cropping system choices.

In general, an increase in cropping frequency is positively correlated with an increase in aggregate stability (Table 14.4). Also, diversified rotations with high-biomass producing crops can be effective for enhancing microbial activity and

Table 14.4 Impacts of intensified no-till cropping systems on soil aggregate stability from studies published in the past 5 year

Location	Crop rotation	Years of intensification	Impacts of intensified cropping systems on aggregate stability	References
Kansas, USA	Sorghum-fallow Continuous sorghum Winter wheat-sorghum-fallow Winter wheat–fallow Continuous winter wheat	33	Continuous wheat increased MWD by 67% compared with sorghum-fallow and wheat-sorghum-fallow in the upper 0.025 m depth	Blanco-Canqui et al. (2010)
Montana, USA†	Winter wheat-fallow Pea-winter wheat Continuous wheat	8	Pea-wheat and continuous wheat increased WSA (> 1 mm) by 49% compared with wheat-fallow	O'Dea et al. (2015)
Colorado, USA‡	Winter wheat-fallow Rotations with fallow every 3 or 4 year Continuous rotations	0–30	Continuous rotations increased MWD by about 45% in the upper 0.10 m depth	Rosenzweig et al. (2018)
Nebraska, USA	Corn-soybean Continuous corn	28	Continuous corn increased MWD by 32% compared with corn soybean in the upper 0.075 m depth	Blanco-Canqui et al. (2014a)
Illinois, USA	Continuous corn Corn-soybean Corn-soybean-winter wheat Continuous soybean	15	No effect in the upper 0.10 m depth	Zuber et al. (2015)

† Soil depth sampling was not specified
‡ Soil was sampled from 96 NT fields in the semi-arid Great Plains, USA

aggregate stability. For instance, in the semiarid US Great Plains, Rosenzweig et al. (2018) reported that adopting NT crop rotations increased fungal biomass in the surface soil by about three times compared with NT crop-fallow systems. Overall, NT continuous cropping or intensified crop rotations with high biomass production can increase aggregate stability relative to NT systems with low biomass production.

14.7 Does Adding Cover Crops to No-Till Soils Improve Aggregate Stability?

Adding cover crops to existing NT cropping systems can be one innovative strategy to enhance aggregate stability. Cover crops provide additional biomass input to NT cropping systems. A review by Blanco-Canqui et al. (2015) found that cover crops can increase aggregate stability by 0–100%, depending on site- and management-specific conditions. Some of the factors that affect cover crop impacts on aggregate stability include:

- Initial soil organic matter
- Cover crop biomass production
- Length of growing season
- Cover crop species
- Fertilization and irrigation
- Time after adoption
- Tillage system
- Seeding rate
- Climate

The amount of biomass produced is one of the most important factors that dictate cover crop benefits. An increase in both aboveground and belowground cover crop biomass typically improves soil C levels and biological activity to improve aggregate stability (Blanco-Canqui et al. 2015). Also, the aboveground biomass protects the soil surface, while the belowground biomass (roots) interact with the soil matrix. High-biomass producing cover crops combined with reduced soil disturbance can improve aggregate stability (Ruis et al. 2019).

The amount of biomass produced by a cover crop is a function of the available growing degree day for cover crop growth. Early planting and late termination can increase cover crop biomass production relative to late-planted and early-terminated cover crops (Ruis et al. 2019). Cover crops planted in summer and terminated in late fall produce more biomass due to favorable temperature and soil moisture conditions than those planted in late fall and terminated in spring, even though the number of days of cover crops in the field for the latter is longer (Blanco-Canqui et al. 2015).

The amount of biomass production also depends on cover crop species. Grass cover crops, such as cereal rye, can be one of the highest biomass producing winter cover crops in temperate regions due to its winter hardiness and rapid establishment (Ruis et al. 2019). Cover crop effectiveness to improve aggregate stability can also increase with time after cover crop adoption. Significant cover crop effect on soil aggregation may require >5 years (Blanco-Canqui et al. 2015). Cover crop biomass production could also increase with increasing seeding rate, fertilization, and irrigation, which can result in improved aggregate stability, although the economics of increased farm input should be considered.

14.8 Does Adding Biochar to No-Till Soils Increase Aggregate Stability?

Applying biochar, a C-enriched material produced from pyrolysis of organic materials, to NT soils can enhance aggregate stability. Biochar application can increase aggregate stability by 3–226% (Blanco-Canqui 2017). Some of the mechanisms by which biochar improves aggregate stability include (Blanco-Canqui 2017; Zhang et al. 2020):

- Biochar contains between 60 and 90% of C, which can enhance aggregation particularly in the long term. The C content in biochar will vary depending on the feedstock and pyrolysis temperature.
- Biochar can improve soil aggregation by adding polyvalent cations and increasing cation exchange capacity. However, if biochar has a high concentration of monovalent cations such as Na^+, it may have limited potential to increase aggregate stability.
- Biochar addition can increase soil biological activity as fungi and bacteria feed on labile C and other organic substances in biochar although biochar commonly contains more stable than labile C. Soil organisms release organic binding agents to increase aggregate stability.
- Biochar can reduce the mineralization of native soil organic matter or C, a process known as negative priming effect. Thus, biochar could increase aggregate stability not only by adding C to soil but also by reducing decomposition of native C. Reduced mineralization of native C can also protect aggregates and reduce their turnover.
- Biochar application can induce a slight water repellency to soil if it has hydrophobic properties. The slow water entry into aggregates can reduce slaking of aggregates.

The effectiveness of biochar to improve aggregate stability can depend on a number of factors including initial soil organic matter, biochar amount, feedstock, pyrolysis temperature, and others. Biochar material with small particle size and high C concentration can more readily and rapidly interact and bind inorganic soil particles than coarse biochar material (Blanco-Canqui 2017). Biochar is also expected to improve aggregate stability more in the long than in short term as biochar particles age and interact with soil matrix (Zhang et al. 2020). Surface application of biochar to NT soils may not allow rapid interaction of biochar particles with soil. Thus, incorporation of biochar through one-time or occasional tillage of NT can be strategy to incorporate biochar into the root zone in NT systems.

14.9 Does Strategic Tillage of No-Till Reduce Aggregate Stability?

In this paper, strategic tillage refers to the one-time tillage of long-term NT soils to manage some of the challenges with NT management, including control of herbicide-resistant weeds, excessive soil compaction, C and nutrient stratification, and acidification. In general, tillage of long-term NT soils once in 5 or 10 years is considered strategic tillage (Wortmann et al. 2010). The few published studies indicate that strategic tillage may or may not reduce aggregate stability (Table 14.5). In cases where strategic tillage reduces aggregate stability, the reduction is short lived

Table 14.5 Effects of one-time or strategic tillage (ST) of otherwise continuous no-till (NT) on soil aggregate stability

Location	Soil	Years under NT	Tillage method	Tillage Depth (m)	Sampling time after ST (years)	Effect of ST on aggregate stability	References
Australia	Three soils	10, 14, and 16	Scarifier or offset discs	0.1	<1	Reduced amount of aggregates (>0.25 mm) by 0–14% in the 0.05 m depth, but returned to initial levels after 1–2 year	Conyers et al. (2019)
Turkey	Clayey	9	Moldboard plow (MP)	0.3–0.33	0	Reduced MWD by 7.2% in the upper 0.1 m depth	Celik et al. (2019)
						Increased MWD by 78% in the 0.1–0.2 m and by 104% in the 0.2–3 m depth	
USA	Two silty clay loams	7–12	MP, miniMP, and chisel or disk	0.1–0.3	<1, 2, and 5	No effect on WSA	Quincke et al. (2007) and Wortmann et al. (2010)

MWD Mean weight diameter of water-stable aggregates, *WAS* Water-stable aggregates

and disappears 1 or 2 years after tillage (Wortmann et al. 2010). In other cases where strategic tillage **r**educes aggregate stability near the soil surface, it increases aggregate stability in the subsoil due to inversion or mixing of surface with subsurface layers. Thus, the sum of changes in aggregate stability for the soil profile due to strategic tillage of NT is generally minimal.

It is important to clarify that while strategic tillage, every 5 or more years, does not generally reduce aggregate stability, more frequent tillage may reduce aggregate stability. For example, Stavi et al. (2011) found that disk plowing of NT every 3 years reduced aggregate stability in a temperate region; however, in the same region, one-time tillage had no effect on aggregate stability when NT soil was tilled once in 10 years (Wortmann et al. 2010). In summary, strategic tillage of long-term NT soils does not appear to have large negative effects on soil aggregate stability, but short-term tillage (<5 years) may reduce aggregate stability.

14.10 Opportunities and Challenges

Opportunities exist to enhance aggregate stability in NT soils through the adoption of cover crops, crop residue management, addition of animal manure and biochar, and intensification of cropping systems with extended rotations or high-biomass producing crops. However, challenges can exist with the use of some companion practices. For instance, cover crop effectiveness depends on the amount of cover crop biomass produced. Cover crops that are planted late or terminated early often produce too little biomass to be of measureable benefit. Also, in water-limited or semiarid regions, cover crops may reduce available water needed for the next crop. A potential opportunity is to use cover crops in low organic matter or degraded NT soils where they can provide more benefits than in high organic matter and productive soils. Targeting low organic matter soils with cover crops can be a better strategy to improve soil properties such as aggregate stability. It is also important to design site-specific cover crop management strategies (i.e., timely planting or termination) to increase cover crop biomass production.

Another opportunity to increase soil C concentration, and thus aggregate stability, is the use of biochar. However, at present, biochar material can be costly and not readily accessible, which limits its use at larger scales. The cost of biochar can be significant when high rates (>10 Mg ha^{-1}) of biochar are often needed to significantly improve aggregate stability and other properties. Also, biochar effects on crop yields have been inconsistent depending on biochar properties, management, and initial soil properties. Similar to cover crop benefits, low organic matter and degraded NT soils may benefit more from biochar application than highly productive NT soils (El-Naggar et al. 2019). Also, identifying the optimum application rates of biochar for different soil types, cropping systems, and climate is a research priority.

Retention of sufficient crop residue is needed to maintain or improve aggregate stability of NT soils. For example, research from the US Midwest shows that excessive crop residue removal can reduce aggregate stability. Indeed, crop residue removal from NT soils could reduce aggregate stability more than residue removal from tilled soils. For example, Laird and Chang (2013) reported that corn residue removal reduced the amount of macroaggregates by 59.5% in NT but only by 13.6% in chisel plow and 30.3% in plow till. Some have suggested that NT soils with limited residue cover, or after complete residue removal, may be equally or more erodible than tilled soils due to reduced aggregate stability (Layton et al. 1993). Estimates from the Midwestern US suggest that about 5 Mg ha^{-1} $year^{-1}$ of crop residues is needed to maintain soil properties in NT fields (Johnson et al. 2014). Additional research is needed to establish threshold levels of residue removal for different soils and climates to manage soil erosion. This means that low-biomass producing NT cropping systems or NT systems where residues are baled should be redesigned to include high-biomass producing crops or cover crops for enhancing aggregate stability.

Furthermore, strategic tillage is proposed as a strategy to address some of the challenges with NT. However, strategic tillage disturbs soil, which could increase risks of water and wind erosion immediately after tillage. Thus, timing of strategic tillage and targeting specific problems will be critical to reduce any potential negative effects. Strategic tillage every 5 or 10 years may not be detrimental to soil properties, but more frequent tillage such as short-term tillage may degrade aggregate stability and other soil structural properties (Quincke et al. 2007; Wortmann et al. 2010; Conyers et al. 2019).

14.11 Conclusions

No-till companion practices differently affect soil aggregate stability. Some companion practices such as inorganic fertilization and strategic tillage do not generally affect soil aggregate stability. Inorganic fertilization increases crop yields, while strategic tillage addresses some of the challenges in long-term NT farming, but these practices do not appear to improve soil aggregate stability. Potential opportunities to increase soil aggregate stability include adoption of cover crops, application of animal manure and biochar, and diversification or intensification of cropping systems. These practices may not come without some challenges, which include the need for redesigning current cropping systems, developing strategies to grow forage or cover crops in water-limited regions, and producing biochar for use at large scales. Also, managing crop residues in NT farming is an essential component. Excessive removal of crop residues through baling or grazing can reduce the ability of NT soils to maintain or improve aggregate stability. In conclusion, maintaining abundant residue cover, growing cover crops, intensifying crop rotations with high-biomass producing crops, and adding animal manure or biochar are some of the potential strategies to enhance structural properties of NT soils, although challenges with adoption of these practices need consideration on a site-specific basis.

References

Adeli A, Brooks JP, Read JJ, Shankle MW, Feng G, Jenkins JN (2019) Poultry litter and cover crop integration into no-till cotton on upland soil. Agron J 111:2097–2107

Aoyama M, Angers DA, N'Dayegamiye A (1999) Particulate and mineral-associated organic matter in water-stable aggregates as affected by mineral fertilizer and manure applications. Can J Soil Sci 79:295–302

Blanco-Canqui H (2017) Biochar and soil physical properties. Soil Sci Soc Am J 81:687–711

Blanco-Canqui H, Lal R (2004) Mechanisms of carbon sequestration in soil aggregates. Crit Rev Plant Sci 23:481–504

Blanco-Canqui H, Ruis S (2018) No-tillage and soil physical environment. Geoderma 326:164–200

Blanco-Canqui H, Schlegel AJ (2013) Implications of inorganic fertilization of irrigated corn on soil properties: lessons learned after 50 years. J Environ Qual 42:861–871

Blanco-Canqui H, Lal R, Shipitalo MJ (2007) Aggregate detachment and wettability and their relationships with organic carbon under long-term land use and management practices. Soil Sci Soc Am J 71:759–765

Blanco-Canqui H, Stone LR, Stahlman PW (2010) Soil response to long-term cropping systems in the central Great Plains. Soil Sci Soc Am J 74:602–611

Blanco-Canqui H, Ferguson RB, Shapiro CA, Drijber RA, Walters DT (2014a) Does inorganic nitrogen fertilization improve soil aggregation? Insights from long-term tillage experiments. J Environ Qual 43:995–1003

Blanco-Canqui H, Ferguson RB, Jin VL, Schmer MR, Wienhold BJ, Tatarko J (2014b) Can cover crop and manure maintain soil properties after Stover removal from irrigated no-till corn? Soil Sci. Soc Am J 78:1368–1377

Blanco-Canqui H, Shaver TM, Lindquist JL, Shapiro CA, Elmore RW, Francis CA, Hergert GW (2015) Cover crops and ecosystem services: insights from studies in temperate soils. Agron J 107:2449–2474

Blanco-Canqui H, Stalker AL, Rasby R, Shaver TM, Drewnoski ME, van Donk S, Kibet LC (2016) Does cattle grazing and baling of corn residue cause runoff losses of sediment, carbon, and nutrients? Soil Sci. Soc Am J 80:168–177

Blanco-Canqui H, Sindelar M, Wortmann CS (2017) Aerial interseeded cover crop and corn residue harvest: soil and crop impacts. Agron J 109:1344–1351

Celik I, Günal H, Acar M, Acir N, Bereket Barut Z, Budak M (2019) Strategic tillage may sustain the benefits of long-term no-till in a vertisol under Mediterranean climate. Soil Tillage Res 185:17–28

Conyers M, van der Rijt V, Oates A, Poile G, Kirkegaard J, Kirkby C (2019) The strategic use of minimum tillage within conservation agriculture in southern New South Wales, Australia. Soil Tillage Res 193:17–26

El-Naggar A, Lee SS, Rinklebe J, Farooq M, Song H, Sarmah AK, Zimmerman AR, Ahmad M, Shaheen SM, Ok YS (2019) Biochar application to low fertility soils: a review of current status, and future prospects. Geoderma 337:536–554

Haynes RJ, Naidu R (1998) Influence of lime, fertilizer and manure application on soil organic matter content and soil physical conditions: a review. Nutr Cycl Agroecosyst 51:123–137

Jiao Y, Whalen JK, Hendershot WH (2006) No-tillage and manure applications increase aggregation and improve nutrient retention in a sandy-loam soil. Geoderma 134:24–33

Jin VL, Schmer MR, Wienhold BJ, Stewart CE, Varvel GE, Sindelar AJ (2015) Twelve years of Stover removal increases soil erosion potential without impacting yield. Soil Sci Soc Am J 79:1169–1178

Johnson JMF, Novak JM, Varvel GE, Stott DE, Osborne SL, Karlen D, Lamb JA, Baker J, Adler PR (2014) Crop residue mass needed to maintain soil organic carbon levels: can it be determined? Bioenergy Res 7:481–490

Kenney I, Blanco-Canqui H, Presley DR, Rice CW, Janssen K, Olson B (2015) Soil and crop response to Stover removal from rainfed and irrigated corn. Global Change Biol Bioenergy 7:219–230

Laird DA, Chang C-W (2013) Long-term impacts of residue harvesting on soil quality. Soil Tillage Res 134:33–40

Layton JB, Skidmore EL, Thompson CA (1993) Winter-associated changes in dry-soil aggregation as influenced by management. Soil Sci Soc Am J 57:1568–1572

O'Dea JK, Jones CA, Zabinski CA, Miller PR, Keren IN (2015) Legume, cropping intensity, and N-fertilization effects on soil attributes and processes from an eight-year-old semiarid wheat system. Nutr Cycl Agroecosyst 102:179–194

Presley DR, Sindelar AJ, Buckley ME, Mengel DB (2012) Long-term nitrogen and tillage effects on soil physical properties under continuous grain sorghum. Agron J 104:749–755

Quincke JA, Wortmann CS, Mamo M, Franti T, Drijber RA, García JP (2007) One-time tillage of no-till systems: soil physical properties phosphorus runoff and crop yield. Agron J 99:1104–1110

Rakkar KM, Blanco-Canqui H (2018) Grazing of crop residues: impacts on soils and crop production. Agric Ecosyst Environ 258:71–90
Rakkar MK, Blanco-Canqui H, Rasby R, Drewnoski ME, Drijber RA (2019) Short-term impacts of cattle grazing and baling of corn residues on soil properties in the central Great Plains. Agron J 111:109–121
Rosenzweig ST, Fonte SJ, Schipanski ME (2018) Intensifying rotations increases soil carbon, fungi, and aggregation in semi-arid agroecosystems agriculture. Ecosyst Environ 258:14–22
Ruis S, Blanco-Canqui H, Burr C, Olson B, Reiman M, Rudnick D, Drijber R, Shaver T (2018) Corn residue baling and grazing impacts on soil carbon stocks and other properties on a Haplustoll. Soil Sci Soc Am J 82:202–213
Ruis SJ, Blanco-Canqui H, Creech CF, Koehler-Cole K, Elmore RW, Francis CA (2019) Cover crop biomass production in temperate agroecozones. Agron J 111:1535–1551
Sindelar M, Blanco-Canqui H, Virginia J, Ferguson R (2019) Cover crops and corn residue removal: impacts on soil hydraulic properties and their relationships with carbon. Soil Sci Soc Am J 83:221–231
Sithole NJ, Magwaza LS, Thibaud GR (2019) Long-term impact of no-till conservation agriculture and N-fertilizer on soil aggregate stability, infiltration and distribution of C in different size fractions. Soil Tillage Res 190:147–156
Stavi I, Lal R, Owens LB (2011) On-farm effects of no-till versus occasional tillage on soil quality and crop yields in eastern Ohio. Agron Sustain Develop 31:475–482
Stewart CE, Roosendaal DL, Sindelar A, Pruessner E, Jin VL, Schmer MR (2019) Does no-tillage mitigate Stover removal in irrigated continuous corn? A multi-location assessment. Soil Sci Soc Am J 83:733–742
Villamil MB, Little J, Nafziger ED (2015) Corn residue, tillage, and nitrogen rate effects on soil properties. Soil Tillage Res 151:61–66
Whalen JK, Chang C (2002) Macroaggregate characteristics in cultivated soils after 25 annual manure applications. Soil Sci Soc Am J 66:1637–1647
Wortmann CS, Shapiro CA (2008) The effects of manure application on soil aggregation. Nutr Cycl Agroecosyst 80:173–180
Wortmann CS, Drijber RA, Franti TG (2010) One-time tillage of no-till crop land five years post-tillage. Agron J 102:1302–1307
Wortmann CS, Klein RN, Shapiro CA (2012) Harvesting crop residues. University of Nebraska-Lincoln extension NebGuide G1846. http://extensionpublications.unl.edu/assets/pdf/g1846.pdf
Wyngaard N, Echeverría HE, Rozas HRS, Divito AG (2012) Fertilization and tillage effects on soil properties and maize yield in a southern pampas Argiudoll. Soil Tillage Res 119:22–30
Zhang Q, Song Y, Wu Z, Yan X, Gunina A, Kuzyakov Y, Xiong Z (2020) Effects of six-year biochar amendment on soil aggregation, crop growth, and nitrogen and phosphorus use efficiencies in a rice-wheat rotation. J Cleaner Production 242:118435
Zuber SM, Behnke GD, Nafziger ED, Villamil MB (2015) Crop rotation and tillage effects on soil physical and chemical properties in Illinois. Agron J 107:971–978