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No-till technology has limited potential to store carbon: How can we enhance such potential?

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A B S T R A C T

No-till is a top soil conservation practice, but if it will be used as a C sequestration strategy, it needs enhancement. Companion practices including N fertilization and irrigation do not often result in net C sequestration or some are unavailable (i.e., biochar) for a large-scale application. Adoption of aggressive or transformative no-till companion practices that genuinely remove CO_2 from the atmosphere through photosynthesis and sequester it in the soil as C should be considered. Enhancing both cover crops and crop rotation complexity can be an aggressive biological strategy to boost no-till performance; yet this has not been much discussed. Enhancing cover crops by increasing both the cropland area under no-till cover crops and cover crop biomass production through biomass yield maximization strategies can store more C in the soil than current no-till cover crop management practices. Additionally, inserting multi-year perennial or forages including grasses and legumes into existing no-till row crop rotations could store an additional amount of C. These no-till enhancement practices may not only increase C sequestration in the soil but also boost the overall resilience and ecosystem services from agricultural lands. Their potential can be particularly greater in low C (below C saturation) than high C (at or near C saturation) no-till soils.

1. Introduction

The potential of no-till farming to sequester atmospheric C in the soil has been questioned (Powlson et al., 2014; VandenBygaart, 2016; White et al., 2018). In cases where no-till accumulates soil organic C (SOC), such gains are not only modest (West and Post, 2002; Powlson et al., 2014; Liang et al., 2020), with an average of about of 0.40 Mg ha^{-1} yr^{-1}, but also highly site-specific. It is important to remember that no-till was not originally designed as a strategy to sequester SOC, but to reduce soil erosion and degradation (Lal et al., 2007). Thus, to expect that no-till can accumulate large amounts of SOC may not be correct. Indeed, no-till as a component of soil conservation practices has delivered its purpose by reducing soil erosion or conserving soil and water since its inception in the 1950s, particularly in the US (Lal et al., 2007). Now, some global initiatives are considering no-till technology as a strategy to accumulate C in agricultural lands (www.4p1000.org). If no-till is to contribute to C sequestration, then it needs significant enhancement. Simply eliminating tillage is not sufficient to capture large amounts of C (Powlson et al., 2014; Blanco-Canqui et al., 2021). This leads to the questions: How can we enhance the potential of no-till to store more C in the soil? How about adding companion practices?

2. Do common no-till companion practices increase soil carbon stocks?

2.1. Nitrogen fertilization

One may expect that N fertilization of no-till soils can rapidly increase SOC stocks by increasing crop residue C production, but what do experimental data show? A literature review using Web of Science of all published studies on N fertilization impacts on SOC accumulation yielded 14 of them. The literature review shows that N fertilization increased SOC stock in seven studies and had no effect in the remaining seven studies (Table 1), indicating that N fertilization can increase SOC stocks in only 50 % of cases. Mean annual SOC accumulation rate across the 14 studies was only 0.13 ± 0.16 Mg ha^{-1} yr^{-1} (mean ± SD). Also, the large standard deviation suggests that fertilization effects on SOC stocks are highly variable.

Biomass production commonly increases with fertilization (Halvorson et al., 1999); however, based on the review, such increase does not translate to gains in SOC stock. This could be due to enhanced residue decomposition from N fertilizer-induced increased activity of soil microorganisms (Stewart et al., 2016). Also, studies show that N fertilization may also maximize aboveground biomass but minimize belowground biomass production (Stewart et al., 2016). Because belowground biomass input is responsible for about 75 % of SOC accrual (Xu et al., 2021), its reduced input could concomitantly result in low

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SOC accumulation.

It is also important to consider that the modest increases in SOC with N fertilization (Table 1) could be undone by the C footprint from manufacturing, transport, and application costs of N fertilizers. Thus, applying N fertilizers does not appear to be an effective companion practice to enhance SOC accumulation in no-till soils. Inorganic fertilization has large agricultural and economic benefits by increasing crop production, but SOC accumulation is not one of the benefits.

2.2. Irrigation

Similar to N fertilization, one may think that irrigation can rapidly increase SOC stocks in no-till soils by increasing crop biomass production. A literature review using Web of Science indicates that irrigation impacts on SOC stocks under no-till management were assessed in only seven study locations (Table 2). Irrigation had no effect on SOC stocks in four and increased in the remaining three study locations when compared with rainfed systems (Table 2). The few available studies indicate thus that irrigation has mixed effects on SOC accumulation. Mean annual SOC accumulation rate across the seven study locations was 0.16 ± 0.10 Mg ha^{-1} yr^{-1}.

The limited effects of irrigation on increasing SOC stocks in spite of increasing biomass production can be explained by the twofold effects of irrigation on SOC balance. While irrigation normally boosts biomass production, periodic soil rewetting increases water content and promotes biological activity, which accelerates the mineralization of crop residues, thereby minimizing SOC build-up (Verma et al., 2005; De Bona et al., 2008). Indeed, fluxes of CO_2 from irrigated soils are often higher than from rainfed systems (Sainju et al., 2008; McGill et al., 2018). Also, losses of dissolved C from the root zone due to frequent irrigation can further reduce SOC gains. Similar to N fertilizer production costs, the small gains in SOC with irrigation could be offset by the energy use associated with pumping groundwater for irrigation and release of CO_2 (Follett, 2001; McGill et al., 2018). Thus, losses of CO_2 can undo the irrigation-induced gains in SOC.

Table 1
A review of all studies on N fertilization effects on soil organic C (SOC) stocks and accumulation rate under no-till management. Because there was no a recent review on this topic, a review of all published studies is presented in this table. Data were estimated from figures when they were not reported in tables.

Location	Crop	Duration (yr)	N rate (kg ha^{-1})	Depth (cm)	SOC (Mg ha^{-1})	Accumulation rate (Mg ha^{-1} yr^{-1})	Reference
Nitrogen Fertilization Increased SOC stocks							
Minnesota, USA	Continuous corn	3	0	0–5	18.0		Sindelar et al., 2014
			200		18.5	0.17	
Nebraska, USA	Continuous corn	9	0	0–30	6.2		Stewart et al., 2015.
			60		10.6	0.49	
			120		12.4	0.69	
Kansas, USA	Continuous corn	50	0	0–30	34.9		Blanco-Canqui et al., 2013
			44.8		39.0	0.08	
			89.6		40.4	0.11	
			134.4		41.3	0.13	
			179.2		42.1	0.14	
			224		44.2	0.19	
Kansas, USA	Sorghum	10	0	0–5	21.8		Presley et al., 2012
			34		23.0		
			67		24.2	0.24	
			135		24.7	0.29	
Alabama, USA	Cotton-corn	10	0	0–20	36.8		Sainju et al., 2008
			100		38.3	0.15	
Rio Grande do Sul, Brazil	Corn-based rotation	18	0	0–20	32.8		Zanatta et al., 2007
			180		34.0	0.07	
Colorado, USA	Spring barley-corn-winter wheat-oat-pea	11	0	7.5	8.2		Halvorson et al., 1999
			22		8.4	0.02	
			45		9.1	0.08	
			67		9.1	0.08	
			90		9.7	0.14	
			134		9.7	0.14	
Nitrogen Fertilization Did not Increase SOC stocks							
China	Wheat-corn	10	0	0–20	27.5		Liu et al., 2020
			25		29.8	0.23	
			50		29.8	0.23	
			75		27.5	0	
			100		28.0	0.05	
KwaZulu-Natal, South Africa	Continuous corn	13	100	0–30	ns	0	Sithole et al., 2019
			200				
Quebec, Canada	Corn-soybean	14	0	0–60	96.0		Poirier et al., 2019
			160		94.0	−0.16	
Kansas, USA	Wheat-shorghum-fallow	50	0	0–7.5	8.3		Mikha et al., 2018
			22		8.6	0.01	
			45		8.7	0.01	
			67		9.8	0.03	
Montana, USA	Barley-pea	7	0	0–85	59.8		Sainju et al., 2014
			134		62.0	0.31	
Balcarce, Argentina	Corn-soybean-wheat	7	0	0–20	19.9		Wyngaard et al., 2012
			150		20.8	0.13	
Saskatchewan, Canada	Wheat-fallow	50	0	0–15	30.32		Lemke et al., 2012
	Wheat-fallow		134		32.8	0.05	
	Wheat-wheat-fallow		0		30.8		
	Wheat-wheat-fallow		134		34.3	0.07	

Table 2
A review of all studies on irrigation effects on soil organic C (SOC) stocks and accumulation rates under no-till management. Because there was no a recent review on this topic, a review of all published studies is presented in this table. Data were estimated from figures when they were not reported in tables.

Location	Precipitation (mm)	Crop	System	Duration (yr)	Depth (cm)	SOC (Mg ha^{-1})	Accumulation rate (Mg ha^{-1} yr^{-1})	Reference
Michigan, USA	1007	Corn-soybean-winter wheat	Rainfed Irrigated	12	0−25	21.5 24.5*	0.25	McGill et al., 2018
North Dakota, USA	373	Malt barley-pea (three rotations)	Rainfed Irrigated	6	0−85	61.7 63.3	0.27	Sainju et al., 2014
Colorado, USA	375	Winter wheat, corn, soybean, and millet	Rainfed Irrigated	38		21.9 28.7*	0.18	Denef et al., 2008
Nebraska, USA	570	Various crops	Rainfed Irrigated	34	0- 20	25.4 27.3*	0.06	
Cordoba, Argentina	757	Corn-wheat	Rainfed Irrigated	11	0−80	35.32 37.75	0.22	Giubergia et al., 2013
Rio Grande do Sul, Brazil	1446	Oat-corn	Irrigated Irrigated	8		32.81 31.77	0.13	De Bona et al., 2008
Nebraska, USA	564	Corn-soybean	Irrigated vs. Rainfed	3	0−30	ns		Verma et al., 2005

* Indicate significant at the 0.05 probability level as reported in each study.

3. How about adding biochar?

Applying biochar, which contains 25–90 % of C depending on the feedstock, is often considered as an effective method to rapidly store C in the soil. Emerging research indicates that biochar has potential to accumulate C and enhance other soil ecosystem services, particularly in degraded and low C soils (Smith, 2016). Also, some laboratory studies suggest biochar can have priming (positive or negative) effects, depending on biochar and soil characteristics (Ding et al., 2018). Negative priming manifests when biochar reduces mineralization of native soil organic matter and crop residues (Ding et al., 2018). One of the first field studies found that woody biochar (9.3 Mg ha^{-1} with 63 % C) applied to no-till cropping systems n a US Midwestern soil increased soil C stocks, but the increase was nearly twice (14.07 Mg soil C ha^{-1}) the amount of C added with biochar (7.25 Mg biochar C ha^{-1}) in the upper 30 cm of soil six years since biochar application (Blanco-Canqui et al., 2020a). This indicates that biochar application to no-till fields can potentially increase soil C stocks not only through direct C input but also through negative priming.

However, at this point, several challenges and trade-offs still exist with the large-scale use of biochar in commercial agriculture. A major limiting factor is the high cost and low availability of biochar. Until more biochar material becomes widely available such as from thermo-chemical biorefineries that produce biochar as a co-product, large-scale application of biochar to no-till croplands will probably remain limited. Also, potential trade-offs of biochar production (biofuel vs. biochar), are yet to be fully understood through a comprehensive life-cycle analysis. Moreover, the conversion efficiency of biomass into biochar can be low. About 50 % of biomass C is lost as CO_2 during pyrolysis (Schlesinger and Amundson, 2019) although the potential negative priming effect of biochar could offset some of the C lost during pyrolysis. Thus, more robust life-cycle analysis as well as long-term field studies across different soil textural classes, initial C levels, and no-till and biochar management scenarios are needed to fully evaluate the mechanisms and extent to which biochar may increase C stocks.

4. How about enhancing practices that genuinely remove CO_2 from the atmosphere?

As discussed above, addition of N fertilizers and irrigation water does not result in a net soil C sequestration (Tables 1 and 2). Similarly, application of animal manure, which is another practice, is simply a transfer of C material from one site to another (Chenu et al., 2019). Also, biochar addition shows promise, but its high cost, limited availability, and potential trade-offs currently hinder its widespread application to no-till croplands. This leads to the question: How about adopting companion practices that can genuinely help no-till soils to sequester C? Enhancing no-till cover crops and crop rotation complexity could be an option.

4.1. Enhancing cover crops

Because several recent reviews are already available on the impacts of cover crops on SOC stocks (Poeplau and Don, 2015; Ruis and Blanco-Canqui, 2017; Jian et al., 2020), this paper does not provide a review on this topic. The reviews reported that cover crops can, in general, sequester <0.56 Mg ha^{-1} yr^{-1} of SOC in the upper 30 cm soil depth. This rate of C sequestration potential by cover crops is relatively small. Aggressive changes in no-till cover crop management strategies are needed to enhance SOC sequestration with cover crops. Two options exist to enhance such potential. The first aggressive option is to increase the current cropland area under cover crop production. Particularly, adding cover crops to environmentally sensitive soils such as sandy, sloping or eroded soils or low initial C soils could sequester larger amounts of SOC than adding to highly productive, fertile, and high C soils. Soils that have lost SOC the most have the largest potential to sequester SOC, depending on management (i.e., amount of cover crop biomass produced), soil (i.e., texture), and climatic (i.e., temperature, moisture) characteristics, among others (Blanco-Canqui et al., 2015; Poeplau and Don, 2015; Jian et al., 2020).

The second aggressive option is to consistently increase the SOC accumulation rate from the current (about 0.56 Mg ha^{-1} yr^{-1}) to rates above 1 Mg ha^{-1} yr^{-1}. For example, sequestering SOC using cover crops at a rate of 2 or 3 Mg ha^{-1} yr^{-1} is not unrealistic (Wiesmeier et al., 2015). However, management of cover crops such as redesigning current cover crop management strategies is critical to consistently achieve this goal. Cover crop biomass input is key. A review of 389 papers reported that cover crop biomass production ranges from 0.87 to 6.30 Mg ha^{-1} with an average of 3.37 ± 2.96 Mg ha^{-1} (Ruis et al., 2019). This indicates that cover crop biomass production and thus C input are highly variable. If a cover crop produces less than 1 Mg ha^{-1} of biomass, then SOC gains can be considered negligible (Blanco-Canqui et al., 2020b).

Under current cover crop management scenarios (i.e., planted late in fall and terminated early in spring), such as those under corn (*Zea mays* L.) and soybean (*Glycine max* L.) systems in the US Midwest, cover crop biomass produced is often < 1 Mg ha^{-1} (Fig. 1A). Maximizing growing degree days (heat units) between cover crop planting and termination through the following aggressive potential strategies is needed to increase cover crop biomass production (Holman et al., 2018; Blanco-Canqui et al., 2020b):

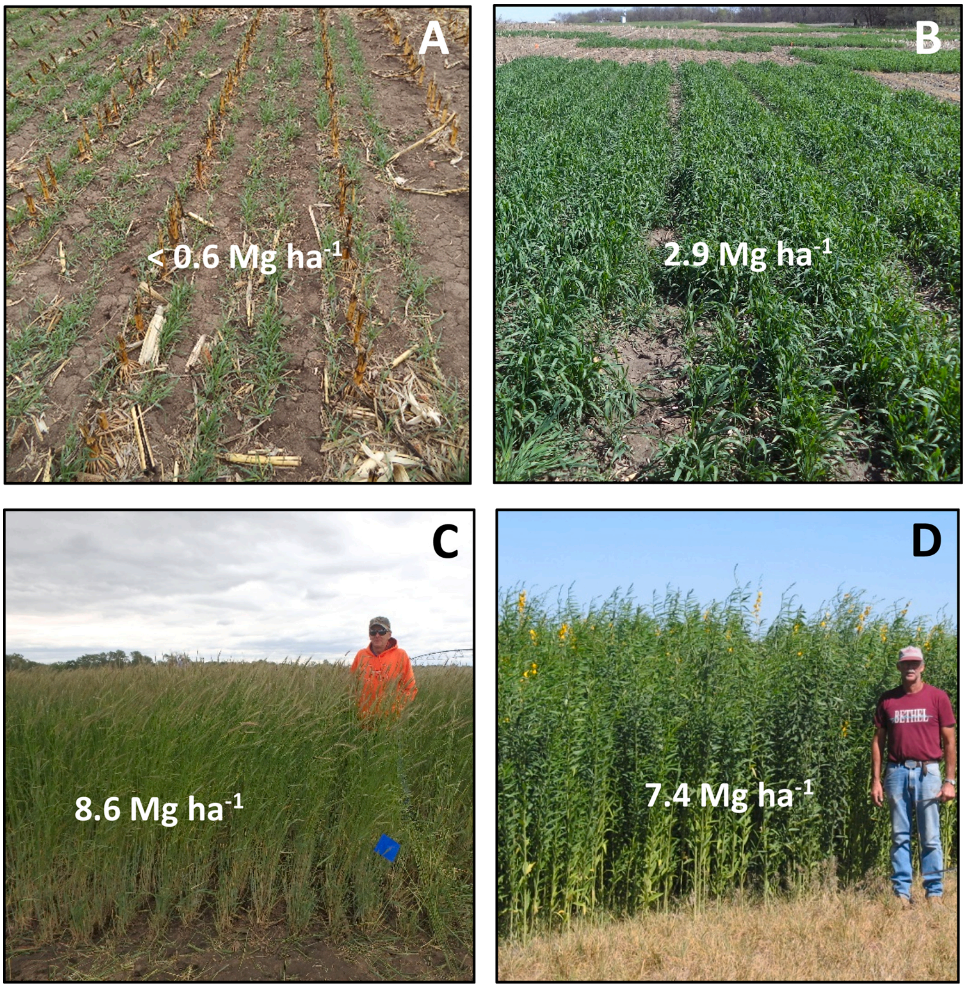

Fig. 1. Examples of how different cover crop management practices determine the amount of biomass produced in temperate regions. A) winter rye (*Secale cereale* L.) cover crop at early termination (i.e., killing) in early April 2015 (30 days before planting corn) when planted in late October of the previous year (a typical winter cover crop management practice in temperate regions), B) winter rye cover crop at late termination (at corn planting) in late April 2015 when planted in late October of the previous year, C) winter rye cover crop in May 2017 when planted in September of the previous year after corn silage harvest, and D) sunn hemp cover crop in October 2007 when planted in July of the same year after winter wheat harvest (Photos by Humberto Blanco).

1) *Planting winter cover crops in late fall after main crop harvest but terminating them late at main crop planting the following spring (Fig. B),*
2) *Planting cover crops in mid or late summer after corn silage or seed corn harvest and terminating them late at main crop planting the following spring (Fig. C),*
3) *Planting cover crops in early or mid summer after harvest of small grains [i.e., winter wheat (Triticum aestivum* L.*)] and terminating them late in fall; Fig. D),*
4) *Interseeding cover crops early into standing main crops using no-till drills and broadcasting.*
5) *Planting cover crops after early maturity crops or double cropping,*
6) *Replacing fallow in crop-fallow systems with cover crops, and*
7) *Incorporating cover crops in flexible crop rotations.*

As an example, these aggressive cover crop management strategies (Fig. 1B through D) can boost biomass production by five to 10 times relative to typical cover crop management practices (Fig. 1A). It is also, however, important to consider additional factors that affect cover crop performance. Such factors include cover crop species selection, time after cover crop adoption, initial SOC level, and climate, among others. First, SOC changes may depend on cover crop species and functional groups although reviews have found some mixed results. Poeplau and Don (2015) concluded that both legume and non-legume cover crops have similar potential to sequester SOC, but Jian et al. (2020) concluded that legume cover crops can sequester more SOC than grass cover crops, Second, SOC sequestration can depend on the length of time after cover crop adoption (Ruis and Blanco-Canqui, 2017). Cover crops could accumulate SOC more in the long (> 3 yr) than in the short term (Blanco-Canqui et al., 2015). Third, as indicated earlier, soils with low initial SOC levels (below C saturation point) can sequester more SOC than high initial SOC soils (at or near C saturation point) (Stewart et al., 2007; Gulde et al., 2008). Thus, successful adoption of cover crops in eroded or degraded soils with C levels could accumulate more SOC than in highly fertile soils with high C levels. Fourth, in regions with low precipitation or semiarid regions, cover crops may reduce water for subsequent crops, thereby reducing crop yields, which will warrant proper cover crop timing. Some studies suggest, however, that cover crops do not generally reduce main crop yields, particularly when precipitation amount is above normal or irrigation water is used for the main crops (Holman et al., 2018; Ruis et al., 2019; Blanco-Canqui et al., 2020b).

Because cover crop adoption is still insufficient due to limited economic returns, harvesting and grazing cover crop biomass for livestock or biofuel production can be a strategy to generate farm profits while simultaneously sequestering SOC (Fae et al., 2009). Indeed, in a review, Blanco-Canqui et al. (2020b) concluded that harvesting cover crops (cutting height of about 7.5 cm) does not reduce the ability of cover crops to sequester SOC nor the delivery of other ecosystem services. It is important to note that grazing or harvesting cover crops does not remove the root biomass, which is more essential than aboveground biomass for sequestering SOC and maintaining other soil ecosystem services (i.e., soil stabilization, improvement in soil properties; Xu et al., 2021). In sum, aggressive cover crop management strategies can be a potential strategy to boost no-till performance for sequestering SOC.

4.2. Enhancing rotation complexity with perennial species

Current no-till row crop rotations do not often sequester large amounts of SOC (West and Post, 2002; Pikul et al., 2008; Dell et al., 2018). Increasing complexity of no-till rotations with forages or perennial grasses can be another aggressive strategy to remove CO_2 from the atmosphere; yet this is little discussed. First, inserting a multi-year perennial forage crop such as a legumes into existing no-till row crop rotations can sequester more SOC than no-till without forages. For example, studies show that including multi-year alfalfa (*Medicago sativa* L.) in corn-soybean rotations could accumulate more SOC than corn-soybean alone, while supporting both crop and livestock production (Pikul et al., 2008; Dell et al., 2018). Including forage legumes can further sequester more SOC by reducing the need for N fertilizers which has a C footprint (Powlson et al., 2016).

Second, inserting perennial grasses into no-till row crop rotations is another option. For example, in the US Corn Belt, growing perennial warm-season grasses such as switchgrass for biofuel on former corn fields for nine years sequestered SOC an average 2 Mg ha^{-1} yr^{-1} at the 0–150 cm soil depth (Follett et al., 2012). This rate of SOC sequestration is about four times higher compared with no-till without multi-year perennial grasses (West and Post, 2002). Also, multi-year perennials, unlike row crops, can sequester about 50 % of SOC at deeper depths in the soil profile due to their deep and extended root systems (Follett et al., 2012). Because most of the SOC contribution from perennials is from roots, aboveground biomass from perennials can be hayed or harvested for livestock and biofuel production without reducing the ability of the system to sequester SOC.

Having perennials continuously for multiple years (>3 yr) in no-till rotations is, however, needed to sequester SOC as their potential to accumulate large amount of SOC in the short term (< 3 yr), similar to cover crops, can be limited. Perennial species could especially fit marginally productive portions of no-till croplands including compacted, poorly drained, eroded, low C, and low fertility soils (Blanco-Canqui, 2016). Also, because soils under no-till often have higher SOC levels near the surface and are closer to C saturation than the subsoil, opportunities exist to promote C sequestration in the subsoil by adding deep-rooted perennials. Note that complex no-till row crops with multi-year perennial forage or biofuel crops not only sequester SOC more than no-till row crop rotation alone, but also enhance the overall resilience and soil ecosystem services from no-till rotations.

5. Conclusions

Adopting aggressive strategies that genuinely remove CO_2 from the atmosphere and boost no-till potential to sequester C is a high priority. Current no-till companion practices (i.e., inorganic fertilization, irrigation) do not directly sequester C from the atmosphere nor increase the potential of no-till to accumulate C in the soil. Biochar shows promise particularly in degraded and sandy or low C no-till soils, but its high cost and limited availability currently hinder its application at large scales. The first aggressive strategy should consist of enhancing cover crops by increasing both cover crop adoption in more no-till croplands and amount of cover crop biomass produced. Increasing the number of growing degree days through inter-seeding early in the main crop growing season; planting in summer after small grain harvest, early maturing crops, and flexible rotations; and replacing fallow with cover crops in crop-fallow systems are some of the innovative strategies to increase biomass production and thereby C input. This strategy could also generate economic returns through cover crop harvesting or grazing cover crops while still enhancing no-till potential to sequester C. The second strategy is by enhancing crop rotation complexity. Adding complexity to current no-till monocrops or row crop rotations by including multi-year (> 3 yr) perennial grasses (i.e., dedicated energy crops) or forages (i.e., legumes) can allow C accumulation not only near the soil surface but also deeper in the soil profile.

It is, however, important to consider that while the above companion strategies could boost no-till potential to sequester SOC by providing additional aboveground and belowground biomass C input, the ability of no-till soils to accumulate SOC will not only depend on the amount of biomass C input but also on the level of C saturation (steady state). The addition of the above practices can accumulate SOC more in low C (below steady state) than in high C (near or at steady state) no-till soils. Once the soil is saturated with C, additional C input will likely accumulate only in labile soil C pools, which are prone to more rapid turnover than stable soil C pools. Additionally, long-term (> 3 yr) addition of the enhanced cover crops and complex rotations will be needed to accumulate C and reach a new steady state level. Overall, the enhanced cover crops and complex rotations combined with no-till technology can sequester more C while improving resilience and soil ecosystem services compared with current no-till practices, particularly in soils with C levels below saturation.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

Blanco-Canqui, H., 2016. Growing dedicated energy crops on marginal lands and ecosystem services. Soil Sci. Soc. Am. J. 80, 845–858.

Blanco-Canqui, H., Shaver, T.M., Lindquist, J.L., Shapiro, C.A., Elmore, R.W., Francis, C. A., Hergert, G.W., 2015. Cover crops and ecosystem services: insights from studies in temperate soils. Agron. J. 107, 2449–2474.

Blanco-Canqui, H., Laird, D.A., Heaton, E., Rathke, S., Acharya, B.S., 2020a. Soil carbon increased by twice the amount of biochar carbon applied after six years: field evidence of negative priming. GCB Bioenergy 12, 240–251.

Blanco-Canqui, H., Ruis, S., Proctor, C., Creech, C., Drewnoski, M., Redfearn, D., 2020b. Harvesting cover crops for biofuel and livestock production: another ecosystem service? Agron. J. 112, 2373–2400.

Blanco-Canqui, H., Shapiro, C.A., Jasa, P., Iqbal, J., 2021. No-till and carbon stocks: is deep soil sampling necessary? Insights from long-term experiments. Soil Tillage Res. 206, 104840.

Chenu, C., Angers, D.A., Barré, P., Derrien, D., Arrouays, D., Balesdent, J., 2019. Increasing organic stocks in agricultural soils: knowledge gaps and potential innovations. Soil Till. Res. 188, 41–52.

De Bona, F.D., Bayer, C., Dieckow, J., Bergamaschi, H., 2008. Soil quality assessed by carbon management index in a subtropical Acrisol subjected to tillage systems and irrigation. Aust. J. Soil Res. 46, 469–475.

Denef, K., Stewart, C.E., Brenner, J., Paustian, K., 2008. Does long-term center-pivot irrigation increase soil carbon stocks in semi-arid agro-ecosystems? Geoderma 145, 121–129.

Ding, F., Van Zwieten, L., Zhang, W.D., Weng, Z., Shi, S.W., Wang, J.K., Meng, J., 2018. A meta-analysis and critical evaluation of influencing factors on soil carbon priming following biochar amendment. J. Soil Sediment 18, 1507–1517.

Follett, R.F., 2001. Soil management concepts and carbon sequestration in cropland soils. Soil Tillage Res. 61, 77–92.

Follett, R.F., Vogel, K.P., Varvel, G.E., Mitchell, R.B., Kimble, J., 2012. Soil carbon sequestration by switchgrass and no-till maize grown for bioenergy. Bioenergy Res. 5, 866–875.

Giubergia, J., Martellotto, E., Lavado, R.S., 2013. Complementary irrigation and direct drilling have little effect on soil organic carbon content in semiarid Argentina. Soil Tillage Res. 134, 147–152.

Gulde, S., Chang, H., Amelung, W., Chang, C., Six, J., 2008. Soil carbon saturation controls labile and stable carbon pool dynamics. Soil Sci. Soc. Am. J. 72, 605–612.

Halvorson, A.D., Reule, C.A., Follett, R.F., 1999. Nitrogen fertilization effects on soil carbon and nitrogen in a dryland cropping system. Soil Sci. Soc. Am. J. 63, 912–917.

Holman, J.D., Arnet, K., Dille, J., Maxwell, S., Obour, A., Roberts, T., 2018. Can cover or forage crops replace fallow in the semiarid Central Great Plains? Crop Sci. 58, 932–944.

Jian, J., Du, X., Reiter, M.S., Stewart, R.D., 2020. A meta-analysis of global cropland soil carbon changes due to cover cropping. Soil Biol. Biochem. 143, 107735.

Lal, R., Reicosky, D.C., Hanson, J.D., 2007. Evolution of the plow over 10,000 years and the rationale for no-till farming. Soil Tillage Res. 93, 1–12.

Lemke, R.L., VandenBygaart, A.J., Campbell, C.A., Lafond, G.P., McConkey, B.G., Grant, B., 2012. Long-term effects of crop rotations and fertilization on soil C and N in a thin Black Chernozem in southeastern Saskatchewan. Can. J. Soil Sci. 92, 449461.

Liang, B.C., VandenBygaart, A.J., MacDonald, J.D., Cerkowniak, D., McConkey, B.G., Desjardins, R.L., Angers, D.A., 2020. Revisiting no-till's impact on soil organic carbon storage in Canada. Soil Tillage Res. 198, 104529.

Liu, Z., Sun, K., Liu, W., Gao, T., Li, G., Han, H., Li, Z., Ning, T., 2020. Responses of soil carbon, nitrogen, and wheat and maize productivity to 10 years of decreased nitrogen fertilizer under contrasting tillage systems. Soil Tillage Res. 196, 104444.
McGill, B.M., Hamilton, S.K., Millar, N., Robertson, G.P., 2018. The greenhouse gas cost of agricultural intensification with groundwater irrigation in a Midwest U.S. row cropping system. Glob. Change Biol. Bioenergy 24, 5948–5960.
Mikha, M.M., Obour, A.K., Holman, J.D., 2018. Soil nutrients status after fifty years of tillage and nitrogen fertilization. Comm. Soil Sci. Plant Anal. 49, 1953–1975.
Poeplau, C., Don, A., 2015. Carbon sequestration in agricultural soils via cultivation of cover crops-A meta-analysis. Agric. Ecosyst. Environ. 200, 33–41.
Poirier, V., Angers, D.A., Rochette, P., Chantigny, M.H., Ziadi, N., 2019. Effects of tillage and mineral fertilization on soil carbon profiles. Soil Sci. Soc. Am. J. 73, 255–261.
Powlson, D.S., Stirling, C.M., Jat, M.L., Gerard, B.G., Palm, C.A., Sanchez, P.A., Cassman, K.G., 2014. Limited potential of no-till agriculture for climate change mitigation. Nat. Clim. Change 4, 678–683.
Powlson, D.S., Stirling, C.M., Jat, M.L., Thierfelder, C., White, R.P., Jate, M.L., 2016. Does conservation agriculture deliver climate change mitigation through soil carbon sequestration in tropical agro-ecosystems? Agric. Ecosyst. Environ. 220, 164–174.
Presley, D.R., Sindelar, A.J., Buckley, M.E., Mengel, D.B., 2012. Long-term nitrogen and tillage effects on soil physical properties under continuous grain sorghum. Agron. J. 104, 749–755.
Ruis, S.J., Blanco-Canqui, H., Creech, C.F., Koehler-Cole, K., Elmore, R.W., Francis, C.A., 2019. Cover crop biomass production in temperate agroecozones. Agron. J. 111, 1535–1551.
Sainju, U.M., Senwo, Z.N., Nyakatawa, E.Z., Tazisong, I.A., Reddy, K.C., 2008. Soil carbon and nitrogen sequestration as affected by long-term tillage, cropping systems, and nitrogen fertilizer sources. Agric. Ecosyst. Environ. 127, 234–240.
Sainju, U.M., Stevens, W.B., Caesar-TonThat, T., 2014. Soil carbon and crop yields affected by irrigation, tillage, cropping system, and nitrogen fertilization. Soil Sci. Soc. Am. J. 78, 936–948.
Schlesinger, W.H., Amundson, R., 2019. Managing for soil carbon sequestration: let's get realistic. Glob. Change Biol. 25, 386–389.
Sindelar, A.J., Lamb, J.A., Coulter, J.A., 2014. Short-term stover, tillage, and nitrogen management affect near-surface soil organic matter. Soil Sci. Soc. Am. J. 79, 251–260.
Sithole, N.J., Magwaza, L.S., Thibaud, G.R., 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.
Smith, P., 2016. Soil carbon sequestration and biochar as negative emission technologies. Glob. Change Biol. 22, 1315–1324.
Stewart, C., Paustian, K., Conant, R., Plante, A., Six, J., 2007. Soil carbon saturation: concept, evidence and evaluation. Biogeochemistry 86, 19–31.
Stewart, C.E., Follett, R.F., Pruessner, E.G., Varvel, G.E., Vogel, K.P., Mitchell, R.B., 2015. Nitrogen and harvest effects on soil properties under rainfed switchgrass and no-till corn over 9 years: implications for soil quality. GCB Bioenergy 7, 288–301.
Stewart, C.E., Follett, R.F., Pruessner, E.G., Varvel, G.E., Vogel, K.P., Mitchell, R.B., 2016. N fertilizer and harvest impacts on bioenergy crop contributions to SOC. GCB Bioenergy 8, 1201–1211.
VandenBygaart, A.J., 2016. The myth that no-till can mitigate global climate change. Agric. Ecosyst. Environ. 216, 98–99.
Verma, S.B., Dobermann, A., Cassman, K.G., Walters, D.T., Knops, J.M., Arkebauer, T.J., Suyker, A.E., Burba, G.G., Amos, B., Yang, H.S., Ginting, D., Hubbard, K.G., Gitelson, A.A., Walter-Shea, E.A., 2005. Annual carbon dioxide exchange in irrigated and rainfed maize-based agroecosystems. Agric. For. Meteorol. 131, 77–96.
West, T.O., Post, W.M., 2002. Soil organic carbon sequestration rates by tillage and crop rotation: a global data analysis. Soil Sci. Soc. Am. J. 66, 1930–1946.
White, R.E., Davidson, B., Lam, S.K., Chen, D., 2018. A critique of the paper "Soil carbon 4 per mille" by Minasny et al. (2017). Geoderma 309, 115–117.
Wiesmeier, M., Lungu, M., Hübner, R., Cerbari, V., 2015. Remediation of degraded arable steppe soils in Moldova using vetch as green manure. Solid Earth 6, 609–620.
Wyngaard, N., Echeverrıa, H.E., Sainz Rozas, H.R., Divito, G.A., 2012. Fertilization and tillage effects on soil properties and maize yield in a Southern Pampas Argiudoll. Soil Tillage Res. 119, 22–30.
Xu, H., Vandecasteele, B., De Neve, S., Boeckx, P., Sleutel, S., 2021. Contribution of above- versus belowground C inputs of maize to soil organic carbon: conclusions from a 13C/12C-resolved resampling campaign of Belgian croplands after two decades. Geoderma 383, 114727.
Zanatta, J.A., Bayer, C., Dieckow, J., Vieira, F.C.B., Mielniczuk, J., 2007. Soil organic carbon accumulation and carbon costs related to tillage, cropping systems and nitrogen fertilization in a subtropical Acrisol. Soil Tillage Res. 94, 510–519.