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Do cover crop mixtures improve soil physical health more than monocultures?

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REVIEW ARTICLE

Do cover crop mixtures improve soil physical health more than monocultures?

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Abstract

Rationale and Purpose — Adding multispecies cover crop (CC) mixtures could diversify the current simplified crop rotations and enhance soil health more than monoculture CCs. Further, CC mixtures with diverse plant species could adapt better to changing climatic and environmental conditions than monoculture CCs. However, our current understanding of the soil benefits of CC mixtures is still limited. This review discussed whether CC mixtures are better than monoculture CCs to improve soil physical health.

Methods — All studies published up to May 25, 2023, comparing soil physical properties between CC mixtures and their constituents grown as monocultures were searched in the available databases. To avoid potential sampling bias, only studies that compared mixtures against all its constituents grown alone were discussed.

Results — Cover crop mixture studies on soil physical properties were relatively few. Mixtures did not reduce soil bulk density in 83% of cases, penetration resistance in 75%, wet aggregate stability in 67%, and dry aggregate stability and saturated hydraulic conductivity in 100% compared with monoculture CCs.

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Mixtures had inconsistent effects on water infiltration and plant available water. The number of CC species in the mixture and management duration do not differently affect mixture impacts. The limited or no differences in soil physical properties between mixtures and monocultures could be due to the similarities in CC biomass production and soil C between these two systems.

Conclusion — Cover crop mixtures do not enhance soil physical properties relative to monoculture CCs in most cases. However, the few cases where mixtures outperformed monocultures suggest soil benefits of mixtures should be evaluated on a site-specific basis. More long-term (> 10 yr) data are needed for more definitive conclusions.

Highlight — Cover crop mixtures do not generally improve soil physical health more than monoculture CCs.

Keywords: Cover crops, Cover crop mixtures, Monocultures, Soil physical health, Soil carbon, Cover crop biomass production

Abbreviation: CC Cover crops

Introduction

Intensive agriculture has reduced biodiversity, homogenized agricultural landscapes, and thus reduced the delivery of multiple regulating, supporting, and provisioning ecosystem services from agricultural lands (Duru et al. 2015; Landis 2017; Tamburini et al. 2020). Restoring biodiversity of current cropping systems is imperative to restore their ability to provide multiple ecosystem services (Tamburini et al. 2020). Adding highly diverse multispecies cover crop (CC) mixtures to existing cropping systems could be a potential strategy to diversify simplified agricultural systems and enhance soil health and services (Chapagain et al. 2020; Waring et al. 2023).

Because each plant species within complex and diverse mixtures can perform different functions or services, it is thought that a mixture of different CC species could be more beneficial to soil health compared with monocultures (Chapagain et al. 2020; Waring et al. 2023). Diverse plant species differ in their rooting depths, canopy characteristics, biomass production, nutrient requirements, and growing conditions, which can differently contribute to their adaptation and survival (Duru et al. 2015; Finney et al. 2016). Furthermore, a monoculture CC can be similar to main crops in terms of resistance to climatic and environmental risks, whereas a mixture of diverse CC species could adapt more successfully to changing or differing climatic and environmental conditions (Smith et al. 2014; Waring et al. 2023).

Published data show that addition of monoculture CCs to monocrops or simplified crop rotations has generally added some diversity and improved soil properties (Schipanski et al. 2014; Blanco-Canqui and Ruis 2020). Thus, one may expect that adoption of highly diverse multispecies CC mixtures could add even more diversification and thus have a greater positive effect on soil health compared with monoculture CCs. Indeed, one often hears during conversations or reads in non-peer reviewed publications that CC mixtures would improve soil health more than monoculture CCs as the former are comprised of diverse plant species.

Soil health is defined as "the continued capacity of soil to function as a vital living ecosystem that sustains plants, animals and humans" (Lehmann et al. 2020). Thus, soil health not only refers to the ability of the soil to support crop production but also to support the health of animals, humans, and the overall ecosystem within the concept of One Health (van Bruggen et al. 2019). Indeed, soil health is the basis for the maintenance and delivery of soil ecosystem services including adaptation to fluctuating climates (i.e., droughts, floods), C and nutrient cycling, retention and transformation of pollutants, and others. Maintaining or improving the health of soils for the continued delivery of soil services is thus imperative. Soil health depends on soil physical health, chemical health, and biological health. One of the key components of the soil health is thus its physical health. However, our current understanding of CC mixture benefits for soil physical health relative to monoculture CCs is limited. Some questions revolving around CC mixtures and soil physical health include:

- Does a diverse CC mixture improve soil physical health more than monocultures?
- Do the soil physical health benefits of CCs mixtures increase as the number of species in a CC mixture increases?
- What are the potential factors (i.e., CC biomass production, climate) that may affect differences (if any) in soil physical health between CC mixtures and monoculture CCs?

An examination of published literature focused on CC mixtures and soil physical health is unavailable to answer the questions above.

A meta-analysis by Florence and McGuire (2020) discussed that CC productivity, weed suppression, N retention, soil water conservation, soil biology, and crop yields between CC mixtures and monocultures did not generally differ, but the review did not specifically discuss soil physical health. Also, a review across all CCs and soil physical properties found that CCs can, in general, improve soil physical properties compared with no CCs, but it did not compare differences in soil physical properties between CC mixtures and monocultures (Blanco-Canqui and Ruis 2020) . Thus, the specific objective of this paper was to review, synthesize, and discuss whether CC mixtures are better than monoculture CCs for improving soil physical health.

All published studies up to May 25, 2023 comparing soil physical properties between CC mixtures and their constituents grown as monocultures were searched in Web of Science and Google Scholar. To avoid potential sampling bias, only studies that compared the CC mixture against all its constituents grown alone were included in this review. Further, only CC mixture studies that included a monoculture CC as a treatment and were under the same tillage system and row crops or vegetables were reviewed. Study or location counts of CC mixtures versus monoculture CCs were employed as a metric to assess whether CC mixtures and monocultures differed in their impacts on soil physical properties. The statistical analysis (e.g., *p-value, LSD*) reported in each paper was used to evaluate whether or not the CC mixtures significantly increased, decreased, or had no effect on soil physical properties compared with monocultures.

Soil physical health

Changes in soil physical, chemical, and biological properties are indicators of changes in soil health (Wood et al. 2017; Lehmann et al. 2020). Thus, soil physical properties are key components of soil health assessment. Some of the common soil physical properties include bulk density, porosity, penetration resistance, wet aggregate stability, water infiltration, saturated hydraulic conductivity, water content at field capacity (-10 to -33 kPa) and -1,500 kPa matric potentials, plant available water, and soil temperature. Soil physical health dictates key soil processes including C sequestration (e.g., C protection in soil aggregates), erosion (e.g., aggregation, water infiltration), and compaction (e.g., bulk density, penetration resistance) risks, exchange and retention of water (e.g., water infiltration, available water), air (e.g., porosity), and heat fluxes in the soil, and root development. As result, discussing whether soil physical properties respond to CC mixtures differently from their response to monoculture CCs can be relevant to understand how CC management affects soil physical health.

Cover crop mixture impacts on soil physical properties

The literature review shows that studies comparing soil physical properties between CC mixtures and their constituents are relatively few (**Tables 1, 2 and 3**). It also shows that only select soil physical properties were studied including soil bulk density, penetration resistance, soil aggregate stability, saturated hydraulic conductivity, and plant available water. Note that more studies on CC mixtures and soil physical properties than those synthesized in Tables 1, 2 and 3 are available in literature. However, the CC mixtures in such studies did not have their constituents present as monocultures in the same experiment for a valid comparison between CC mixtures and monocultures. Thus, as mentioned earlier, these studies were not included in this review. Just as an example, a study comparing CC mixture of tap-rooted and fibrous-rooted species against only fibrous species grown as monocultures in the experiment may conclude that CC mixture reduced soil compaction risks more than monoculture CCs due to the biodrilling effect of tap-rooted species. However, such conclusion would be incorrect as the CC mixture was not compared against tap-rooted CC grown alone in the same experiment.

Soil compaction parameters

Soil bulk density and penetration resistance are indicators of soil porosity, compaction risks, root penetration, and water, gas, and heat flux rates, and other soil dynamic processes. In general, a reduction in bulk density and penetration resistance can have positive effects on the above processes. The review found 6 studies on soil bulk density and 4 studies on penetration resistance (Table 1). It indicates that

CC mixtures did not significantly reduce soil bulk density in 5 of the 6 studies (83% of cases) compared with monoculture CCs. Similarly, CC mixtures did not significantly reduce penetration resistance in 3 of the 4 studies (75% of cases) compared with monoculture CCs. The synthesis of available literature indicates that CC mixtures do not improve soil bulk density and penetration resistance compared with monoculture CCs in most cases (> 75% of cases).

The review also indicates that, in a few cases (< 25% of cases; Table 1), CC mixtures may have beneficial effects on soil bulk density (Stavi et al. 2012) and penetration resistance (Decker et al. 2022) relative to monocultures. While most studies show no significant effect of CC mixtures, the reduction in soil bulk density and penetration resistance in the few cases suggests that the effects of CC mixtures should be assessed on a site-specific basis. For instance, in the few cases where CC mixtures reduced soil bulk density and penetration resistance, the mixtures included radish CC (Table 1), which suggests that mixtures containing brassicas (tap-rooted CCs) could alleviate soil compaction risks more than monocultures, potentially due to the biodrilling effect of tap-rooted CC species.

Mixing fibrous-rooted CCs with tap-rooted CCs may complement each other to reduce compaction risks. A few studies investigated root characteristics (i.e., length, diameter) between CC mixtures and monocultures (Yu et al. 2016; Bukovsky-Reyes et al. 2019; Saleem et al. 2020). While CC mixtures do not consistently have greater root diameter and length than monocultures (Yu et al. 2016; Bukovsky-Reyes et al. 2019), a pot experiment in the greenhouse found some species in a CC mixture had larger root area and longer roots compared with monocultures, which is attributed to competition among CC species (Saleem et al. 2020). The greenhouse study evaluated crimson clover (*Trifolium incarnatum*), chickling vetch (*Vicia villosa*), field peas (*Pisum sativum*), hairy vetch (*Vicia villosa*), mighty mustard (*Brassica juncea*), and oilseed radish (*Raphanus sativus*), four 3-way mixtures, and a mixture of 6 species. Field studies are needed to better comprehend differences in root architecture between mixtures and monocultures that may develop as a result of potential competition and complementarity of roots within CC mixtures (Gastine et al. 2003). In general, data available to this point indicate CC mixtures do not appear to alleviate soil compaction more than monocultures in most cases.

Table 1 Impact of cover crop (CC) mixtures on soil bulk density and penetration resistance compared with monoculture CCs under different soil textural classes, climates, years in CC, and CC species.

Location	*Soil Texture*	*MAP (mm)*	*MAT (°C)*	*Years in CC*	*Cover Crops*	*Depth (cm)*	*CC Mixture* Impact	Reference
Bulk Density								
New Mexico, U.S 2022	Clay loam	462	14.0	5	Pea, oat, canola vs. Mixtures	0–20	ns	Acharya et al.
Ardabili, Iran	Loam	333	14.3	2	Barley,chickling pea, and buckwheat vs. Mixture	0–15	ns	Ghahremani et al. 2021
Iowa, U.S	Silt loam	834	9.2	6	Rye and Oat vs. Mixture	0–5	ns	Kaspar et al. 2006
Kansas, U.S	Loam, silt loam, and silty clay loam	903	11.9	3	Radish and wheat vs Mixture	0–10	ns	Crossman 2019
Illinois, U.S	Silt loam	1045	10.9	5	Rye and hairy vetch vs. Mixture	0–5	ns	Villamil et al. 2006
Ohio, U.S	Silt loam	917	10.0	0.75	Austrian winter pea and radish vs Mixture	0–10	Reduced or had no effect	Stavi et al. 2012
Penetration Resistance								
Ridgetown, Canada	Sandy loam	724	9.6	8	Oat, radish, and rye vs Radish-rye	0–15	ns	Chahal and Van Eerd 2019
Illinois, U.S	Silt loam	1045	10.9	5	Rye and hairy vetch vs. Mixture	0–30	ns	Villamil et al. 2006
Alabama, U.S	Loamy sand	1397	18.5	4	Rye, clover, and radish vs Mixtures	0–50	Increased or had no effect	Decker et al. 2022
Alabama, U.S	Silt loam	1440	18.0	4	Rye, clover, radish vs Mixtures	0–50	Reduced or had no effect	Decker et al 2022

MAP = mean annual precipitation, MAT = mean annual temperature, ns = non-significant

Table 2 Impact of cover crop (CC) mixtures on soil aggregate stability compared with monoculture CCs under different soil textural classes, climates, years in CC, and CC species.

Location	*Soil Texture*	*MAP (mm)*	*MAT (°C)*	*Years in CC*	*Cover Crops*	*Depth (cm)*	*CC Mixture* Impact	Reference
Wet-Aggregate Stability								
Alabama, U.S	Loamy sand	1440	18.0	4	Rye, clover, and radish vs Mixtures	0–5	ns	Decker et al. 2022
Alabama, U.S	Silt loam	1397	18.5	4	Rye, clover, and radish vs Mixtures	0–5	ns	
New Mexico, U.S	Clay loam	248	15.3	3	Barley, mustard, and pea vs Mixture	0–20	ns	Agarwal et al. 2022
New Mexico, U.S		248	16.8	2	(Mustard, rye, Vetch) vs Mixtures	0–20	ns	Antosh et al. 2020
New Mexico, U.S		248	13.1	2	(Mustard, rye, Vetch) vs Mixtures	0–20	ns	
Illinois, U.S	Silt loam	1045	10.9	5	(Rye or hairy vetch) vs Mixture	0–30	ns	Villamil et al. 2006
New Mexico, U.S	Loam	250	13.1	3	Barley, mustard, and pea vs Mixture	0–20	Reduced or had no effect	Agarwal et al. 2022
Ridgetown, Canada	Sandy loam	724	9.6	8	Oat, radish, and rye vs Radish-rye	0–15	Increased or had no effect	Chahal and Van Eerd 2019
Ohio, U.S	Silt loam	917	10.0	0.75	Austrian winter pea and radish vs Mixture	0–10	Increased or had no effect	Stavi et al. 2012

Location	*Soil Texture*	*MAP (mm)*	*MAT (°C)*	*Years in CC*	*Cover Crops*	*Depth (cm)*	*CC Mixture* Impact	Reference
Dry-Aggregate Stability								
New Mexico, U.S	Loam	250	13.3	3	Barley, mustard, and pea vs Mixture	0–20	ns	Agarwal et al 2022
.New Mexico, U.S	Clay loam	229	15.3	3	Barley, mustard, and pea vs Mixture	0–20	ns	
New Mexico, U.S	Clay loam	248	16.8	2	(Mustard, Rye, Vetch) vs Mixtures	0–20	ns	Antosh et al. 2020
New Mexico, U.S	Loam	248	13.1	2	(Mustard, Rye, Vetch) vs Mixtures	0–20	ns	

MAP = mean annual precipitation, MAT = mean annual temperature, ns = non-significant

Table 3 Impact of cover crop (CC) mixtures on soil hydraulic properties compared with monoculture CCs under different soil textural classes, climates, years in CC, and CC species.

Location	*Soil Texture*	*MAP (mm)*	*MAT (°C)*	*Years in CC*	*Cover Crops*	*Depth (cm)*	*CC Mixture* Impact	Reference
Water Infiltration								
Ardabili, Iran	Loam	333	14.3	2	Barley, chickling pea, and buckwheat vs. Mixture	0–15	Increased or no effect	Ghahremani et al. 2021
Saturated Hydraulic Conductivity								
Illinois, U.S	Silt loam	1045	10.9	5	Rye or hairy vetch vs. Mixture	0–30	ns	Villamil et al. 2006
Ohio, U.S	Silt loam	917	10.0	0.75	Austrian winter pea or radish) vs. Mixture	0–10	ns	Stavi et al. 2012
Plant Available Water								
Ridgetown, Canada	Sandy loam	724	9.6	8	Oat, radish, and rye vs. Radish-rye	0–15	ns	Chahal and Van Eerd 2019
Santa Fe, Argentina	Silt loam	1019	17.5	6	Wheat, oat, vetch vs. Oat-vetch	0–200	Reduced	Duval et al. 2016
Illinois, U.S	Silt loam	1045	10.9	5	Rye or hairy vetch vs. Mixture	0–30	Increased or no effect	Villamil et al. 2006
Kansas, U.S	Silt loam	489	12.1	5	Hairy vetch, winter pea, spring pea, winter triticale, spring triticale, spring lentil vs. Mixtures	0–200	Increased or no effect	Holman et al. 2018

MAP = mean annual precipitation, MAT = mean annual temperature, ns = non-significant

Soil structural properties

Wet and dry aggregate stability are the leading indicators of changes in soil structural health. Soil aggregation determines soil strength, macroporosity, microbial activity, energy fluxes, root growth, C sequestration, and other processes. Literature review found 7 CC mixture studies on wet aggregate stability and 2 on dry aggregate stability (Table 2). However, some studies on wet and dry aggregate stability had more than one study location within the same study (Table 2). Thus, location counts instead of studies are used in this review to discuss CC mixture impacts on soil aggregate stability. Wet aggregate stability was examined in 9 study locations, while dry aggregate stability in 4 locations (Table 2). Cover crop mixtures had no effect in 6 of the 9 locations for wet aggregate stability (67%) and all locations (100%) for dry aggregate stability compared with monocultures. These results indicate that, similar to soil bulk density and penetration resistance, CC mixtures did not improve soil aggregate stability in most situations.

While CC mixtures had no effect on wet aggregate stability in most locations (67%), they increased, reduced or had no effect on wet aggregate stability in the remaining locations (33%) relative to monocultures (Table 2). The latter results suggest that CC mixtures can have some inconsistent effects in one-third of cases. The increase in wet aggregate stability with mixtures in 2 of the 9 locations can be promising (Table 2). It is interesting to note that, in cases where mixtures increased wet aggregate stability, the mixtures included fibrous- and tap-rooted CCs, suggesting potential facilitation between these two species (Stavi et al. 2012; Chahal and Van Eerd 2019). Results suggest fibrous-rooted species [e.g., rye (*Secale cereale* L.), pea] and tap-rooted (e.g., radish) species may assist each other (root complementarity) to explore the soil matrix and promote soil aggregation relative to monocultures (Stavi et al. 2012). The results also suggest that opportunities may exist to promote soil aggregation with mixtures in a few cases, but such potential benefits deserve a site-specific assessment of mixture impacts.

However, the lack of improvement in dry aggregate stability under CC mixtures appears to corroborate the limited or no response of dry aggregate stability to CC introduction in general. A review of studies across all CCs found that CCs do not generally improve soil dry aggregate stability compared with no CCs (Blanco-Canqui and Ruis 2020). Yet, changes in dry soil aggregate stability are an indicator of soil resistance to wind erosion. An increase in soil dry aggregate size with CC mixtures would indicate reduced wind erosion potential. While the 2 field studies on dry aggregate stability showed no advantage of CC mixtures over monocultures, a pot experiment reported that proportion of meso-aggregates (250 to 500 μm) increased while proportion of microaggregates (< 250 μm) decreased as plant diversity gradient increased (Saleem et al. 2020). This suggests that CC mixtures can improve soil aggregation in some cases. Additional data on dry aggregate stability under mixtures and monocultures from field experiments are needed to further understand where and when mixtures can improve dry aggregate stability and thus reduce wind erosion potential more than monocultures. Overall, available studies indicate that CC mixtures may not improve soil aggregation compared with monocultures in most cases.

Soil hydraulic properties

Improving soil hydraulic properties including water infiltration, saturated and unsaturated hydraulic conductivity, and water retention (e.g., plant available water) is key to the movement, storage, and overall management of precipitation water and hydrology. The review found 1 study on water infiltration, 2 studies on saturated hydraulic conductivity and 4 on plant available water (Table 3). Cover crop mixtures had no effect on saturated hydraulic conductivity in both studies (100%), but they had mixed effects on water infiltration and plant available water. Cover crop mixtures increased or had no effect on water infiltration, while they increased, decreased, and had no effect on plant available water (Table 3). These results indicate that CC mixtures can have inconsistent impacts on soil water movement and retention.

The lack of consistent impacts of CC mixtures on soil water capture and storage has implications for soil water management. For example, in water-limited regions, concerns exist that growing CCs can reduce available water for the following main crops (Unger and Vigil 1998; Nielsen et al. 2015). Some may consider that a mixture of diverse CC species could use less water than monocultures through reciprocal facilitation among CC species relative to monocultures. However, research data do not entirely support this consideration (Nielsen et al. 2015; Khan and McVay 2019). The increase in plant available water with CC mixtures in a few cases (Table 3) suggest the discussion or identification of factors that may influence the positive impacts of CC mixtures on soil hydraulic properties in select cases.

Potential factors governing cover crop mixture performance

Aboveground and belowground biomass production Aboveground biomass production of CCs is one of the key parameters that affects CC impacts on soil health and ecosystem services. Potential differences in biomass production between CC mixtures and monoculture CCs could induce differences in soil physical properties. However, a meta-analysis by Florence and McGuire (2020) comparing CC mixtures against all their constituents present as monocultures found aboveground CC biomass production between CC mixtures and monocultures did not differ in 90% of comparisons.

Cover crop mixtures do not often outperform high-biomass producing monoculture CCs (Florence and McGuire 2020). This suggests that differences in biomass production could be driven more by the different plant species themselves than by competition and complementarity in the mixture (Gastine et al. 2003). For example, grass CCs such as cereal rye often dominate when mixed with brassicas and legumes species (Koehler-Cole et al. 2020). Results further suggest that increased species diversity or richness under CC mixtures does not always translate into greater CC biomass production nor greater improvement in soil physical health relative to monocultures. Thus, the similarities in aboveground CC biomass production between mixtures and monocultures may explain the mixed or no effects of CC mixtures on soil physical properties found in the present review (Tables 1, 2 and 3).

The follow-up question is: How about belowground (root) biomass production under CC mixtures? Do CC mixtures yield more root biomass than monocultures? The importance of roots for the improvement and maintenance of soil physical, chemical, and biological environment is well recognized (Freschet et al. 2021). Indeed, belowground CC biomass can be more relevant to soil erosion control (Yu et al. 2016) and soil C accumulation than aboveground biomass (Xu et al. 2021). Yu et al. (2016) found that differences in root length and root diameter among CC species can be the best predictors of changes in soil hydraulic conductivity and runoff amount. They found that CCs with coarse and dense roots increased soil hydraulic conductivity and reduced surface runoff by 17%. Thus, any differences in root biomass production between CC mixtures and monocultures could determine the extent to which CC mixtures affect soil physical properties. However, the few field studies on CC mixtures that characterized CC root biomass found that CC mixtures do not produce more root biomass than monocultures (Fae et al. 2009; Bukovsky- Reyes et al. 2019). Thus, belowground CC biomass production, similar to aboveground biomass production, between CC mixtures and monocultures does not often differ.

Soil carbon

Soil organic C is one of the dynamic drivers of soil aggregation, macropore development, water transmission, and other soil physical processes (Blanco- Canqui et al. 2013). Cover crops are considered a potential management practice to sequester C in the soil and restore some of the C lost due to intensive cultivation (Poeplau and Don 2015; Jian et al. 2020; McClelland et al. 2021). However, similar to the lack of differences in CC biomass production, CC mixtures do not often increase soil C concentration and stocks relative to monocultures. A review by Florence and McGuire (2020) concluded that soil C between CC mixtures and their monocultures does not significantly differ in 94% of comparisons. Thus, the limited impacts of CC mixtures on physical properties as compared with monocultures can be partly explained by the lack of differences in soil C levels between mixtures and monocultures. There may be a few cases where CC mixtures accrue more soil C than monocultures (Saleem et al. 2020), but evidence to state that mixtures consistently accumulate or sequester more soil C than monoculture is insufficient based on the available research data.

Further, initial soil C concentration could affect impacts of CC mixtures on soil physical health. Soils with low initial C concentration may benefit more from the addition of diverse CC species than soils with high initial C concentration. Most of the available studies on CC mixtures were, however, conducted in soils with high initial C concentration and in temperate regions. These studies showed small or no impacts of CC mixtures on soil physical health. Two short-term studies provide some insights into how differences in initial soil C concentration may affect CC mixture performance. A multi-site study conducted in South Dakota, U.S. found that grass, broadleaf, and grass/broadleaf CC mixtures did not significantly affect soil health parameters after one growing season when the experiment was established in soils with 4.10% of organic matter (2.4% C) concentration (Bielenberg et al. 2023). However, a study conducted in Iran found that chickling pea (*Lathyrus sativus* L.) + barley (*Hordeum vulgare* L.) and buckwheat (*Fagopyrum esculentum* Moench) + barley CC mixtures increased water infiltration compared with buckwheat CC and no CC in a soil with 1.03% organic matter (0.6% C) after two growing seasons (Ghahremani et al. 2021). These few studies from soils with contrasting organic matter levels suggest CC mixtures can improve soil properties more in soils with low initial C than in those with high initial C concentration. Particularly soils under long-term (> 10-yr) no-till management can have higher soil C concentration in the upper 5 or 10 cm soil surface relative to intensively plowed soils. The high initial C level in some no-till soils can delay or limit soil benefits from CCs. More data from soils with contrasting levels of soil C are needed to elucidate the extent to which differences in initial soil C concentration affect soil benefits of CC mixtures and monocultures.

Seeding rate

Increasing the CC seeding rates often increases CC biomass production (Koehler-Cole et al. 2020; Waring et al. 2023). In the few cases where CC mixtures produce more biomass than monocultures, the increased CC biomass production may be partly due to high seeding rates used for mixtures. The opposite can also be true when low seeding rates are used for mixtures (Waring et al. 2023). Thus, differences in CC seeding rates can be a potential confounding factor when comparing impacts of mixtures and monocultures on CC biomass production and thus soil physical health. In a review, Florence and McGuire

(2020) found that CC mixtures can produce more biomass than monocultures in 2% of comparisons and not in 98% of comparisons, but the increased biomass in the 2% of comparisons was confounded with the effect of high seeding rate under CC mixtures.

Accounting for the differences in seeding rates between CC mixtures and monocultures among studies can be important to better discern CC mixture impacts. Under real world conditions, seeding rates for CC mixture are often adjusted or altered after CC adoption to help with CC success, but this alteration in seeding rates can make the comparison of impacts of mixtures and monocultures on soil physical health difficult (Antosh et al. 2020). Developing optimum seeding rates for CC mixtures and monocultures is a research need. Currently, seeding rates within mixtures are often determined by dividing the monoculture seeding rate over the number of CC species in the mixture.

Cover crop species

While available literature indicates CC mixtures generally do not improve soil physical health more than monocultures, in a few cases, CC mixtures can be better than monocultures. One factor that may affect such superiority can be the type of CC species in the mixture (Ghahremani et al. 2021). For example, combining grasses and legume CCs may perform better than some constituents or other mixtures (Murrell et al. 2017). In Alabama, U.S., cereal rye–clover CC mixture produced more biomass compared with clover, radish, and clover–radish mixture in 1 of 2 sites (Decker et al. 2022). Adding grass CCs to a mixture can thus increase CC biomass production relative to other CCs. In Ohio, U.S., Stavi et al. (2012) found that Austrian winter peas + radish CC mixture improved soil properties more than radish but did not differ from Austrian winter peas. As discussed earlier, brassicas could likely benefit from the addition of CCs with fibrous roots for improving soil properties. Cover crop mixtures may develop different root characteristics (e.g., diameter, length) through the potential facilitation or complementarity among CC species. The different root characteristics with CC mixtures may manifest in differences in some soil properties (e.g., penetration resistance), which deserves further assessment. Thus, performance of CC mixtures can depend on the proper selection of CC species for the mixtures.

Number of cover crop species in the mixture

It is often thought that increasing the number of species in a CC mixture would increase the soil benefits of mixtures (Khan and McVay 2019). The few studies that evaluated changes in soil physical properties under 2-way, 3-way, and other multiple combinations of CCs indicate that the number of species in the mixture does not differently affect soil physical properties (Holman et al. 2018; Antosh et al. 2020; Acharya et al. 2022; Decker et al. 2022). Most studies have evaluated 2-way combinations of CCs. In the few cases when mixtures increase CC biomass production and improve some soil properties, changes appear to occur under 2 to 4 CC species in the mixture. Thus, 2 to 4 species in a CC mix may be the "optimum" number of species for a mixture, depending on the multifunctionality of CC species in the mixtures (Murrell et al. 2017; Bybee-Finley et al. 2022). A systematic long-term assessment of multiple combinations of CCs within the same study can help with the identification of the right combinations to improve soil physical health.

Time after introduction of cover crop mixtures

Time after CC adoption can be an important parameter that could influence the extent to which CCs affect changes in soil properties. For example, many soil physical properties are slow to change and significant changes may not be observed in the short term (< 5 yr). According to Tables 1, 2 and 3, duration of the CC mixture experiments in the studies available ranged from 2 to 8 yr. Long-term (> 10 yr) experiments under CC mixtures are unavailable to fully understand how CC mixtures and monocultures compare in their impacts on soil physical health. The available medium-term (5–8 yr) studies in Tables 1, 2 and 3 indicate that management duration of CCs, similar to other factors, appears to have limited influence on how CC mixtures affect soil physical health relative to monocultures in the medium term. However, the potential factors affecting performance of CC mixtures most probably interact. No single factor can fully explain impacts of CC mixtures. For example, in a few cases, CC mixtures may significantly improve soil properties even in the short term (< 2 yr) when soil initial C level is low (Ghahremani et al. 2021). In general, low C soils could rapidly respond to CC introduction and biomass C input.

Fluctuations in weather

Fluctuations in precipitation and temperature from year to year often have greater influence on CC biomass production than CC species or CC mixtures (Antosh et al. 2020; Agarwal et al. 2022). However, it is considered CC mixtures may be less subject to year-to-year variability in weather than monocultures due to the inclusion of diverse CC species in mixtures (Khan and McVay 2019; Waring et al. 2023). Inclusion of different CC species in mixtures can allow natural selection of best-performing CC species within mixtures under fluctuating climates (Waring et al. 2023). In temperate regions, cereal rye and triticale are some of the grass CC species that dominate other species within mixtures. In addition to annual fluctuations in weather, rotation phase of the main crops can also contribute to the variability in CC biomass production from year to year. For instance, crops receiving limited or no fertilization within a rotation can deplete nutrients in the soil and reduce biomass production of the subsequent CCs (Agarwal et al. 2022). Conducting long-term CC studies can be valuable to better understand how fluctuations in weather affect CC biomass production between mixtures and monocultures.

Research needs

A number of research needs remain for a robust comparison of changes in soil physical properties between CC mixtures and monocultures:

1. While many have compared soil physical properties between CC mixtures against monoculture CCs, about 50% of studies did not have all the constituents grown as monocultures within the same experiment needed for valid comparisons. A need thus exists to conduct additional studies of CC mixture with all its components grown as monocultures across different environments and CC management scenarios for more valid conclusions. It is worth noting that if the purpose is sustainable intensification for nutrient management, mixing different CC species (legumes and non-legumes) without having their counterparts grown as monocultures could be methodologically valid to obtain species-specific benefits. For example, non-legume CCs such as cereal rye can scavenge nutrients,

while legume CCs can fix N from the atmosphere (Antosh et al. 2020). Indeed, most of the published studies on CC mixtures have focused on soil fertility improvement or nutrient availability for the subsequent crops. However, the relatively few studies comparing CC mixtures against their constituents grown as monocultures do not support the idea that mixing CC species (e.g., legumes vs non-legumes) for nutrient management would also benefit soil physical health.

2. Most of the published studies comparing CC mixtures against monoculture CCs are short term (< 5 yr). If the goal of establishing CC mixtures with diverse plant species is to somewhat mimic natural systems, which have been in place for many decades or centuries, then CC mixtures many need to be planted year after year for many decades within the same study location to detect any positive effects of CC mixtures in the long-term (> 10 yr). Conducting long-term studies on CC mixtures and monocultures does not come, however, without challenges including cost (e.g., seed, equipment), time, labor, and management skills (Clay et al. 2020). For instance, most funding agencies provide financial support for short-term (3 or 4 yr) projects. The short-term studies do not allow sufficient time for a robust understanding of how CC mixtures and monocultures may impact soil health and soil ecosystem services in the long term. Especially, management induced changes in soil physical properties are often measurable in the long term. Long-term funding and extended cost-share programs can be valuable to implement long-term CC studies and assess the potential benefits and tradeoffs between CC mixtures and monocultures.

3. Furthermore, in natural systems, diverse plant species (i.e., perennials) grow for most of the year. In contrast, CCs including mixtures are often grown for a few months between main crops, which may be too short to fully capture any potential benefits from CC mixtures. Extending CC growing season by planting early (interseeding) or planting after short-season cash crops could be a strategy to enhance biomass production from CCs and better discern if CC mixtures outperform monoculture CCs.

4. While many reported data on aboveground CC biomass production under CC mixtures (see the review by Florence and McGuire

2020), limited or no information exists on how CC mixtures affect the belowground biomass production. Available data indicate that CC mixtures do not increase aboveground biomass production over monoculture CCs in most cases (Florence and McGuire 2020), but the same cannot be concluded about belowground CC biomass production response when experimental data are few. The limited data on belowground (root) CC biomass in literature can be partly attributed to the challenges associated with root assessment methods unlike with aboveground biomass assessment methods. The available methods for root biomass quantification, which include mechanical (i.e., hydropneumatic elutriation system) washing, and hand washing are often time-consuming and laborious. Also, it is often difficult to accurately quantify CC root biomass in the soil. For example, fine roots, which are the largest fraction of roots under young plants such as CCs grown for a few months, cannot be easily identified or separated from the soil and other crop roots during measurements.

5. Most studies on CC mixtures have been conducted in regions with high precipitation (> 500 mm). Additional CC mixture studies from different climatic regions are needed to further evaluate whether CC mixtures are better than monocultures across contrasting regions, particularly in the long term.

6. Cover crop mixture studies often focus on CC biomass production and main crop yields. Data on soil physical and hydraulic properties, which affect many soil services (i.e., erosion, productivity) are limited under different scenarios of CC mixture management.

7. Research on CC species complementarity within a CC mixture is needed to better understand how functions from diverse CC species can enhance soil physical properties and thus soil health from CC mixtures as compared with monocultures. Simply mixing CC species without a full understanding of how each CC species would contribute to some collective soil service such as soil physical health may not fulfill a specific desired goal from CC mixtures.

8. Increasing the CC seeding rates can increase CC biomass production up to an optimum level. However, an increase in CC seeding rate increases seed costs and total CC production costs. Also, CC seeding rate depends on CC species. For example, grass CCs are often

commonly planted at higher seeding rates than other CC species. Thus, identifying the optimum seeding rate for CC species for each mixture and monoculture is a need to maximize CC biomass production while reducing CC production costs. The optimum seeding rates should be identified for multiple combinations of CCs in mixtures including 2-way, 3-way, and 4-way combinations.

Conclusions

Available research data at this point do not appear to support the idea that increasing diversity of CC species in a mixture will enhance soil physical properties and thus soil physical health relative to monoculture CCs. When CC mixture is compared with all its constituents present as monocultures, CC mixtures do not reduce bulk density and penetration resistance nor increase saturated hydraulic conductivity, and available water in most studies. The lack of positive CC mixture effects on soil physical health relative to monocultures in most situations suggests that the diversity-productivity theory from ecology indicating that diverse plant species would deliver more services and improve soil properties more than monocultures may not fully apply to CC mixtures in most cases (Tilman 1999; Isbell et al. 2015). Cover crop mixtures differ from perennial diverse plant species in that CC mixtures are composed of annual species and often grown for a few months relative to perennial species. In agreement with some of the individual studies on CC mixtures, this review suggests that if the goal is to enhance soil physical health, planting high-biomass producing monoculture CCs could be more cost effective than diverse and costly CC mixtures.

The limited or no effects of CC mixtures in soil physical health may be due to the similarities in CC biomass production and soil organic C concentration between mixtures and monocultures. Also, the number of CC species in the mixture, duration, climate, and other factors do not appear to affect differences between mixtures and monocultures, but additional long-term (> 10 yr) research data are needed to better understand potential factors affecting CC mixture performance. Moreover, because the magnitude of response or no response of soil properties depended on the CC mixture comparison type, future studies should only compare CC mixture against all its constituents present as monocultures within the experiment for valid conclusions. Additionally, the results in the present review showing that CC mixtures can have some benefits over monocultures in a few cases suggest that soil benefits of CC mixtures should be evaluated on a field- or site-specific basis. Overall, review of published literature indicates that CC mixtures do not generally improve soil physical health more than monoculture CCs.

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References

Acharya P, Ghimire R, Cho Y, Thapa VR, Sainju UM (2022) Soil profile carbon, nitrogen, and crop yields affected by cover crops in semiarid regions. Nutr Cycl Agroecosyst. https://doi.org/10.1007/s10705-022-10198-1

Agarwal P, Lehnhoff EA, Steiner RL, Idowu OJ (2022) Cover Crops Enhance Soil Properties in Arid Agroecosytem despite Limited Irrigation. Agronomy (Basel) 12:1235

Antosh E, Idowu J, Schutte B, Lehnhoff E (2020) Winter cover crops effects on soil properties and sweet corn yield in semi-arid irrigated systems. Agron J 112:92–106

Bielenberg H, Clark JD, Sanyal D, Wolthuizen J, Karki D, Rahal A, Bly A (2023) Cover crop composition in longterm no-till soils in semi-arid environments do not influence soil health measurements after one year. Soil Sci Soc Am J. https://doi.org/10.1002/saj2.20523

Blanco-Canqui H, Ruis SJ (2020) Cover crop impacts on soil physical properties: A review. Soil Sci Soc Am J 84:1527–1576

Blanco-Canqui H, Shapiro CA, Wortmann CS, Drijber RA, Mamo MM, Shaver TM, Ferguson RB (2013) Soil organic carbon: The value to soil properties. J Soil Water Conserv 68:129A-134A

Bukovsky-Reyes S, Isaac ME, Blesh J (2019) Effects of intercropping and soil properties on root functional traits of cover crops. Agric Ecosyst Environ 285:106614

Bybee-Finley AK, Cordeau S, Yvoz S, Mirsky SB, Ryan MR (2022) Finding the right mix: a framework for selecting seeding rates for cover crop mixtures. Ecol Appl 32:e02484. https://doi.org/10.1002/eap.2484

Chahal I, Van Eerd LL (2019) Quantifying soil quality in a horticultural- cover cropping system. Geoderma 352:38–48

Chapagain T, Lee EA, Raizada MN (2020) The potential of multi-species mixtures to diversify cover crop benefits. Sustainability 12:2058

Clay L, Perkins K, Motallebi M, Plastina A, Farmaha BS (2020) The perceived benefits, challenges, and environmental effects of cover crop implementation in South Carolina. Agriculture 10:372

Crossman S (2019) Short-term effects of cover crops on soil health and yield in established no-till systems. MSc Thesis. Kansas State University, Manhattan, KS

Decker HL, Gamble AV, Balkcom KS, Johnson AM, Hull NR (2022) Cover crop monocultures and mixtures affect soil health indicators and crop yield in the Southeast United States. Soil Sci Soc Amer J 86:1312–1326

Duru M, Therond O, Martin G, Martin-Clouaire R, Magne MA, Justes E, Journet EP, Aubertot JN, Savary S, Bergez JE, Sarthou JP (2015) How to implement biodiversity-based agriculture to enhance ecosystem services: A review. Agron Sust Devel 35:1259–2128

Duval ME, Galantini JA, Capurro JE, Martinez JM (2016) Winter cover crops in soybean monoculture: effects on soil organic carbon and its fractions. Soil Tillage Res 161:95–105

Fae GS, Sulc RM, Barker DJ, Dick RP, Eastridge ML, Lorenz N (2009) Integrating winter annual forages into a no-till corn silage system. Agron J 101:1286–1296

Finney DM, White CM, Kaye JP (2016) Biomass production and carbon/nitrogen ratio influence ecosystem services from cover crop mixtures. Agron J 108:39–52

Florence AM, McGuire AM (2020) Do diverse cover crop mixtures perform better than monocultures? A systematic review. Agron J 112:3513–3534

Freschet GT, Roumet C, Comas LH, Weemstra M, Bengough AG, Rewald B, Bardgett RD, De Deyn GB, Johnson D, Klimešová J, Lukac M, McCormack ML, Meier IC, Pagès L, Poorter H, Prieto I, Wurzburger N, Zadworny M, Bagniewska-Zadworna A, Blancaflor EB, Brunner I, Gessler A, Hobbie SE, Iversen CM, Mommer L, Picon-Cochard C, Postma JA, Rose L, Ryser P, Scherer-Lorenzen M, Soudzilovskaia NA, Sun T, Valverde-Barrantes OJ, Weigelt A, York LM, Stokes A (2021) Root traits as drivers of plant and ecosystem functioning: current understanding, pitfalls and future research needs. New Phytol 232(3):1123–1158. https://doi.org/10.1111/nph.17072

Gastine A, Scherer-Lorenzen M, Leadley PW (2003) No consistent effects of plant diversity on root biomass, soil biota and soil abiotic conditions in temperate grassland communities. Applied Soil Ecol 24:101–111

Ghahremani S, Ebadi A, Tobeh A, Hashemi M, Sedghi M, Gholipoouri A, Barker AV (2021) Short-term impact of monocultured and mixed cover crops on soil properties, weed suppression, and lettuce yield. Commun Soil Sci Plant Anal 52:406–415

Holman JD, Arnet K, Dille J, Maxwell S, Obour A, Roberts T, Roozeboom K, Schlegel A (2018) Can cover or forage crops replace fallow in the semiarid central Great Plains? Crop Sci 58:932–944

Isbell F, Craven D, Connolly J, Loreau M, Schmid B, Beierkuhnlein C, Bezemer TM, Bonin C, Bruelheide H, de Luca E, Ebeling A, Griffin JN, Guo Q, Hautier Y, Hector A, Jentsch A, Kreyling J, Lanta V, Manning P, Meyer ST, Mori AS, Naeem S, Niklaus PA, Polley HW, Reich PB, Roscher C, Seabloom EW, Smith MD, Thakur MP, Tilman D, Tracy BF, van der Putten W, van Ruijeven J, Weigelt A, Weisser WW, Wilsey B, Eisenhauer N (2015) Biodiversity increases the resistance of ecosystem productivity to climate extremes. Nature 526:574-U263

Jian J, Du X, Reiter MS, Stewart RD (2020) A meta-analysis of global cropland soil carbon changes due to cover cropping. Soil Biol Biochem 143:107735

Kaspar TC, Parkin TB, Jaynes DB, Cambardella CA, Meek DW, Jung YS (2006) Examining changes in soil organic carbon with oat and rye cover crops using terrain covariates. Soil Sci Soc Am J 70:1168–1177

Khan QA, McVay KA (2019) Productivity and stability of multi-species cover crop mixtures in the northern Great Plains. Agron J 111:1817–1827

Koehler-Cole K, Elmore RW, Blanco-Canqui H, Francis CA, Shapiro CA, Proctor CA, Ruis SJ, Heeren DM, Irmak S, Ferguson RB (2020) Cover crop productivity and subsequent soybean yield in the western Corn Belt. Agron J 112:2649–2663

Landis DA (2017) Designing agricultural landscapes for biodiversity- based ecosystem services. Basic Appl Ecol 18:1–12

Lehmann J, Bossio DA, Kögel-Knabner I, Rillig MC (2020) The concept and future prospects of soil health. Nat Rev Earth Environ 1:544–553

McClelland SC, Paustian K, Schipanksi ME (2021) Management of cover crops in temperate climates influences soil organic carbon stocks — a meta-analysis. Ecol Appl 31:e02278

Murrell EG, Schipanski ME, Finney DM, Hunter MC, Burgess M, LaChance JC, Baraibar B, White CM, Mortensen DA, Kaye JP (2017) Achieving diverse cover crop mixtures: effects of planting date and seeding rate. Agron J 109:259–271

Nielsen DC, Lyon DJ, Hergert GW, Higgins RK, Calderon FJ, Vigil MF (2015) Cover crop mixtures do not use water differently than single-species plantings. Agron J 107:1025–1038

Poeplau C, Don A (2015) Carbon sequestration in agricultural soils via cultivation of cover crops – A meta-analysis. Agric Ecosys Environ 220:33–41

Saleem M, Pervaiz ZH, Contreras J, Lindenberger JH, Hupp BM, Chen D, Zhang Q, Wang C, Twigg P (2020) Cover crop diversity improves multiple soil properties via altering root architectural traits. Rhizosphere 16:100248

Schipanski ME, Barbercheck ME, Douglas MR, Finney DM, Haider K, Kaye JP, Kemanian AR, Mortensen DA, Ryan MR, Tooker J, White C (2014) A framework for evaluating ecosystem services provided by cover crops in agroecosystems. Agric Syst 125:12–22

Smith RG, Atwood LW, Warren ND (2014) Increased productivity of a cover crop mixture is not associated with enhanced agroecosystem services. PLoS One 9:e97351

Stavi I, Lal R, Jones S, Reeder R (2012) Implications of cover crops for soil quality and geodiversity in a humid-temperate region in the Midwestern USA. Land Degrad Dev 23:322–330

Tamburini G, Bommarco R, Wanger TC, Kremen C, van der Heijden MGA, Liebman M, Hallin S (2020) Agricultural diversification promotes multiple ecosystem services without compromising yield. Sci Adv 6:eaba1715

Tilman D (1999) The ecological consequences of changes in biodiversity: A search for general principles. Ecology 80:1455–1474

Unger PW, Vigil MF (1998) Cover crop effects on soil water relationships. J Soil Water Conserv 53:200–207

van Bruggen AHC, Goss EM, Havelaar A, van Diepeningen AD, Finckh MR, Morris JG (2019) One Health - Cycling of diverse microbial communities as a connecting force for soil, plant, animal, human and ecosystem health. Sci Total Environ 664:927–937

Villamil MB, Bollero GA, Darmody RG, Simmons FW, Bullock DG (2006) No-till corn/soybean systems including winter cover crops: Effects on soil properties. Soil Sci Soc Am J 70:1936–1944

Waring E, Licht M, Ripley E, Staudt A, Carlson S, Helmers M (2023) Cover crop mixtures versus single species Water quality and cash crop yield. J Soil Water Conserv 78:1–15

Wood M, Litterick AM, Goss M (2017) Soil health – What should the doctor order? Soil Use Manag 33:339–345

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 $^{13}C/^{12}C$-resolved resampling campaign of Belgian croplands after two decades. Geoderma 383:114727

Yu Y, Loiskandl W, Kaul HP, Himmelbauer M, Wei W, Chen L, Bodner G (2016) Estimation of runoff mitigation by morphologically different cover crop root systems. J Hydrology 538:667–676