frontiers | Frontiers in Sustainable Food Systems

TYPE Editorial
PUBLISHED 05 December 2023
DOI 10.3389/fsufs.2023.1320870

OPEN ACCESS

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RECEIVED 13 October 2023
ACCEPTED 09 November 2023
PUBLISHED 05 December 2023

CITATION
Reilly EC, Conway-Anderson A, Franco JG, Jungers JM, Moore EB and Williams C (2023) Editorial: Continuous living cover: adaptive strategies for putting regenerative agriculture into practice.
Front. Sustain. Food Syst. 7:1320870.
doi: 10.3389/fsufs.2023.1320870

Editorial: Continuous living cover: adaptive strategies for putting regenerative agriculture into practice

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KEYWORDS

sustainable agriculture, cover crops, perennial agriculture, climate smart, agroforestry, winter annuals, conservation agriculture, continuous living cover

Editorial on the Research Topic
Continuous living cover: adaptive strategies for putting regenerative agriculture into practice

Introduction

Continuous Living Cover (CLC) is a term used to describe agricultural systems that include year-round vegetative cover above ground and living roots below ground. Examples of CLC include agroforestry, perennial biomass, perennial forages and grazing lands, perennial grains, and systems of summer and winter annuals and cover crops managed to maximize soil coverage (Jewett and Schroeder, 2015; Chrisman et al., 2021). Continuous Living Cover offers a framework for studying and implementing agricultural strategies that keep land in production while maintaining or enhancing soil and water quality in the long term. These strategies promote a diversified agricultural landscape and can be combined in myriad ways to help farmers achieve both economic and environmental goals.

Strategies for achieving CLC addressed in this Research Topic include spring planted winter cereal rye (*Secale cereale L.*) interseeded with soybeans (*Glycine max* (L.) Merr). (Brockmueller et al.), pennycress (*Thlaspi arvense L.*) relay-cropped with soybeans (Gesch et al.), silvopasture systems (Mayerfeld et al.), perennial grains (Chamberlain et al.; Pinto et al.; Reilly et al.; Cureton et al.; Mulla et al.), perennial forages (Chamberlain et al.; McPheeters et al.), perennial grasslands (Audia et al.; Wepking et al.; Rissman et al.), and cover crops (Ingram; Koehler-Cole et al.; Myers and Wilson; Nichols and MacKenzie; Thompson et al.). While CLC can be employed on a global scale, most of the research in this Research Topic was conducted in the context of the predominant cropping systems in the Midwestern United States, but conclusions are suitable for broader geographies and agroecological systems.

History of the CLC concept

Continuous Living Cover strategies have been used since ancient times. Virgil's (c 29 BCE) writings reference diverse annual rotations, legume cover crops, animal integration and reduced tillage, noting their beneficial effects on soil (Mackail, 1950). North American Indigenous agriculture has long integrated perennial and annual polycultures, intercropping, animals, and agroforestry (Salmón, 2012; Carlisle, 2022; Nabhan et al., 2022; Kapayou et al., 2023). Benefits of these agricultural practices include stabilizing crop yields over time, soil health enhancement, crop pest and pathogen management, and weed reduction, all of which have been reported since at least 1939 (Blake, 1939) and supported by scientific literature since at least the 1980s (Lewandowski, 1987; Rossier and Lake, 2014; Mueller et al., 2019), though they have been observed by practitioners for much longer.

In the early 2000s, a coalition of partners across the U.S. Upper Midwest, including the Green Lands Blue Waters steering committee, was looking for a term to convey the sustainable agriculture practices and goals they wanted to promote. They initially used "continuous cover" and "conservation cover" before arriving at "Continuous Living Cover", which became an umbrella term around which others began organizing (Aaron Reser, personal communication, June 25, 2023; Jeff Berg, personal communication, June 30, 2023). The term appears in titles and keywords of scientific literature from 2010 (Jordan and Warner, 2010), and in U.S. government agency funding and support beginning slightly later (e.g., SARE, 2014).

The benefits of CLC systems in the U.S. Upper Midwest are relatively well-documented (Feyereisen et al., 2006; Basche and DeLonge, 2017; Franco et al., 2018, 2021a; Liebig et al., 2018; Jungers et al., 2019; Reilly et al.), and a renewed interest in them has been brought about by the continuing dominance of low diversity, input-intensive cropping systems and the adverse impacts associated with them.

Rationale

There is an urgent need for agriculture systems that keep land in production while preserving soil and water quality, providing wildlife habitat, and limiting greenhouse gas emissions. In the U.S. Upper Midwest, summer annual row crops have replaced much of the historical native forests and prairies (Schulte et al., 2006; Liebman and Schulte, 2015) that built deep soils and supported diverse ecosystems. The current agricultural paradigm is supported by federal policy, notably crop insurance, along with well-developed infrastructure and supply chains, technical assistance, industry interests, and dominant narratives about American agriculture (Boody et al., 2005; Jordan et al., 2007). For example, agricultural subsidies totaled $276.1 billion from 1995 to 2021, the majority of which supported a few annual commodity crops including corn (*Zea mays L.*), soybeans, wheat, and cotton (*Gossypium hirsutum L.*) (EWG, 2023). While modern row crop agriculture produces high yields, it also results in negative externalities which are well-documented and widespread (Boody and DeVore, 2006; Davis et al., 2012; Liebman and Schulte, 2015).

Rates of soil erosion from farm fields in the U.S. Midwest are 10–1,000 times higher than natural systems (Quarrier et al., 2023), resulting in the loss of an estimated ∼57.6 billion tons of soil over the past 150 years (Thaler et al., 2022), as well as large losses of soil organic carbon (Sanford et al., 2012; Sanderman et al., 2017). Widespread nitrogen fertilizer continues to contribute to the hypoxic zone in the Gulf of Mexico (Rabalais and Turner, 2019), nitrate leaching into groundwater, and formation of the potent greenhouse gas nitrous oxide (Wang and Li, 2019), threatening human health, ecosystem function, and long-term climate stability. Globally, the food system is the largest driver of biodiversity loss and continues to threaten species as land is converted to agricultural uses (Williams et al., 2020; Knapp and Sciarretta, 2023). Consolidation has also led to fewer, larger farms and decreased diversity of farm owners (USDA, 2019; Congressional Research Service, 2021).

Continuous Living Cover systems offer an evidence-based avenue to address these challenges. They facilitate longer periods of crop growth that maximize solar energy use, minimize erosion and nutrient loss, support greater wildlife diversity, incorporate more crop and livestock species, and provide socioeconomic benefits such as diversified income streams (Boody et al., 2005; Jordan et al., 2007; Davis et al., 2012; Tamburini et al., 2020). In addition, by increasing soil organic matter, CLC systems can increase soil water retention, conferring greater resilience to floods and droughts that are becoming more common due to climate change (Hatfield and Dold, 2017; Lal, 2020; Berdeni et al., 2021). Some practices, especially agroforestry and managed grazing, can increase soil organic carbon and could be avenues for agricultural carbon sequestration (Becker et al., 2022; Mayer et al., 2022). Several articles in this Research Topic further describe ecosystem-scale soil, water, and habitat benefits from CLC strategies (Audia et al.; Reilly et al.; Chamberlain et al.; Wepking et al.). There is also evidence that diversified CLC systems can improve agronomic outcomes including yield, yield stability, and weed and pest suppression (Davis et al., 2012; Isbell et al., 2017; Tamburini et al., 2020).

Scientific basis for CLC

The science of CLC is firmly rooted in ecology. Soil ecosystems require energy and nutrient inputs, the means for nutrient cycling and nutrient loss minimization, and protection from degradative forces. Inputs must be of a biochemical diversity commensurate with the diverse types of ecophysiology and ecological life strategies found in these systems. In short, the scientific basis of CLC is supported by four foundational concepts: functional biodiversity, rhizosphere activity, year-round surface cover, and minimal disturbance.

Functional biodiversity

Functional biodiversity is the collective of organismal and ecological traits that increase overall ecosystem service provisions, resistance, and resilience (Tilman et al., 1997, 2014; Loreau et al., 2001; Hooper et al., 2005). A growing body of literature speaks to the importance of functional biodiversity to agroecosystems. Adding to the functional biodiversity of cropping systems has been shown to enhance productivity (Franco et al., 2015), yield stability

(Khan and McVay, 2019; Franco et al., 2021b), and substantially increase soil health metrics (McDaniel et al., 2014; Costa et al., 2018; Sprunger et al., 2020). Articles in this Research Topic also highlight how functional biodiversity can increase crop pest suppression [Brockmueller et al.; Bruce et al.(b)], retain nutrients (Wepking et al.), and augment soil water retention (Nichols et al., 2022; Moore, 2023).

Rhizosphere activity

Temporal and spatial expansion of the rhizosphere, along with associated rhizodeposition, microbial activity, and nutrient cycling, have been shown to support soil health and ecosystem functioning (Neumann, 2007; Moore et al., 2014; Reilly et al.). Root exudates seem to disproportionately influence soil microbial community composition (Dennis et al., 2010) and soil organic matter cycling (Sokol et al., 2019) more so than shoot or root decomposition. Kelly et al. (2022) found that crop root exudates were a main factor in determining soil microbial community composition, as well as nitrogen cycling. Other microbes such as arbuscular mycorrhizal fungi that inhabit the rhizosphere are also critical in nutrient cycling and enhancing crop resiliency in response to abiotic stressors (Begum et al., 2019). Another example from research in this Research Topic showed that a perennial grain crop had higher root biomass compared to annual crops, and that this root biomass was likely associated with nitrate leaching reductions in the perennial crop (Reilly et al.).

Year-round surface cover

Year-round cover on the soil surface substantially attenuates wind and water erosion. Incorporation of living cover, such as perennial grass (Acharya et al., 2019) and agroforestry systems (Sauer et al., 2021), have been shown to be effective in reducing sediment transport compared to conventional row crop systems. Additionally, dead or decomposing cover, such as crop residues, can also reduce erosion (Kaspar and Singer, 2011) and improve soil structural stability (Kahlon et al., 2013).

Minimal disturbance

Minimizing disturbance, namely tillage, facilitates functional biodiversity, rhizosphere activity, and perennial surface cover. Soil structure (Kahlon et al., 2013), soil ecological community composition (Mathew et al., 2012), and water flow (Zhang et al., 2017) can vary significantly as a function of tillage. As such, no-tillage and reduced tillage management systems serve to facilitate many of the soil ecosystem services detailed herein.

Challenges and barriers to adoption

While Continuous Living Cover strategies offer many environmental benefits, adoption has been slow. For instance, although cover crop usage has increased by 50% from 2012 (4.2 million ha) to 2017 (6.3 million ha), cover crops were used on only 3.9% of total U.S. cropland (USDA, 2019).

Some challenges are related to the climate. In the U.S. Upper Midwest and other cold climates, the short growing season and limited planting window after harvest of summer annual crops have necessitated research on cover crop interseeding, which has yet to produce consistent results, limiting its use by growers. Even in corn silage production systems, which have a shorter seeding-to-harvest window than corn harvested for grain, cover crops should generally be planted on or before September 15 to provide the greatest benefits (Feyereisen et al., 2006), leaving little time for establishment and biomass production.

Slow adoption is also a result of lack of policy support and incentives (Rissman et al.), as well as limited availability of technical assistance (Cureton et al.). For example, while the United States Department of Agriculture (USDA) Natural Resources Conservation Service (NRCS) encourages year-round cover through practices like cover cropping and intercropping, the Risk Management Agency imposes varying planting limitations for insurance eligibility (NRCS, 2014, 2019; RMA, 2019). Further, though cover crop cost share funding is sometimes available, it may not adequately compensate the farmer for the cost of seed, planting, and potential yield reductions, meaning that implementation may entail personal income loss (Plastina et al., 2018). When CLC practices are incentivized, adoption increases. For example, participation in an incentive program doubled average cover crop acreage among farmers in the Northeastern United States, a region with similar climatic challenges to the U.S. Upper Midwest (Chami et al., 2023).

Another factor is variability and trade-offs in on-farm performance due to regional or other factors, a topic addressed by several of the articles in this Research Topic. For example, Brockmueller et al. observed more variability in yields of organic soybeans with an interseeded rye living mulch compared to the tilled control. Effective weed suppression depended on having enough soil moisture for sufficient rye biomass production, thus, soil moisture influences the success of this CLC practice. Bruce et al.(a) demonstrated that cover crops and reduced tillage management of organic squash (*Cucurbita pepo* L.) resulted in trade-offs: weed pressure was reduced, but yield was also reduced and there was a similar negative outcome on pest pressure. Other work by Bruce et al.(b) shows how living cover crop mulches can reduce both pest and weed pressures, but may also reduce crop yield. Similarly, soybean-pennycress relay systems show promise, but require more regional adaptation research (Gesch et al.).

Also addressed by this literature is one of the challenges for broader CLC adoption, the fact that the factors that affect the scope, extent, or rate of improvement are not well-identified, so it is difficult to predict conditions for the greatest success. Modeling helps to illustrate these dynamics. Grass bioenergy crops strategically integrated into an Iowa watershed could provide ecosystem services, but projected watershed-wide revenues ranged from −$44.2 to $128.8 million (Audia et al.). This variability in outcomes, whether it is the magnitude of improvement or simply trade-offs between positive and negative effects, is a key limiting factor in widespread adoption (Ingram) because it creates a high-risk decision-making environment for producers, compounded in some cases by increased management needs. For example, top concerns reported by non-adopter farmers in a national farmer survey about adopting cover crops were related to variability in system performance (Myers and Wilson). Potential reduction in crop yields and economic returns, and poor stand establishment were second only to the additional time and labor needed to manage an integrated system with cover crops.

A theme that appears throughout this Research Topic is concern about on-farm performance being compounded by the disconnect between institutional resources and support as research attempts to gain a deeper understanding of the nuances in performance of these systems. Koehler-Cole et al. note a significant discrepancy in outcomes in cover crop research between controlled, replicated researcher-led trials and "real world" performance in farmer-led trials, indicating a need for more of the latter. A survey of Wisconsin farmers using cover crops also identified needs for more regionally-specific information, which is deeply entwined with availability of research, as well as better contextualized data—the "story" behind the numbers (Ingram). Though these challenges exist, CLC practices can also be implemented with few apparent downsides. For example, intercropping Kernza (*Thinopyrum intermedium* [Host] Barkworth & D.R. Dewey), perennial grain with legumes increased forage value without decreasing grain yield (Pinto et al.). Reduced tillage didn't affect the profitability of conventional or organic systems (Pearsons et al.), and occasional tillage could reduce herbicide reliance without harming soil health when combined with cover crops and perennial grains (McPheeters et al.).

The existence of successful CLC systems, ongoing challenges, and the growing interest among farmers (Mayerfeld et al.) underscores the need for continued research efforts to assess which factors influence outcomes under different conditions, as well as for improved policy and technical assistance to encourage adoption and manage risk. This requires building a deeper understanding of agroecological interactions in order to provide practitioners with nuanced recommendations, which can help generate more reliable performance and make the increased effort a worthwhile investment.

Putting CLC into action

Implementing multifunctional agriculture systems built on CLC practices will require ongoing research, consistent communication of technical information to producers, development of relevant enterprises to support sustainable commercialization, and reshaping public policy and opinion (Boody and DeVore, 2006; Jordan and Warner, 2010; Liebman and Schulte, 2015; Jordan et al., 2016). Each article in this Research Topic offers insight from a different perspective into how CLC adoption could be expanded.

Foundational research continues to demonstrate how CLC can achieve the goals of many different stakeholders (Chamberlain et al.; Reilly et al.; Mayerfeld et al.). As research on CLC crops and strategies advances, the findings can be translated into applied practices and tested by researchers and early-adopter growers to determine how to integrate them into conventional cropping systems (Gesch et al.; Koehler-Cole et al.). Underutilized strategies can help identify research needs (Nichols and MacKenzie), which in some cases should be expanded to on-farm experimentation at a range of scales (Koehler-Cole et al.).

As more empirical data are generated from experiments and on-farm studies, researchers can model where to best promote specific CLC practices for optimized economic and agronomic outcomes (Audia et al.). Innovative strategies such as remote sensing can pinpoint hotspots of adoption, providing useful insights (Thompson et al.). Throughout the development and testing process, researchers also must measure the economic and environmental implications of CLC implementation (e.g., Pearsons et al.; Pinto et al.).

Grower adoption and successful marketing of CLC crops requires effective, ongoing communication between farmers, researchers, intermediaries, technical service providers, policy makers, and food processors (Jordan et al.; Conway). Empirical data and models are important for guiding policy recommendations to support grower adoption of CLC (Mulla et al.; Thompson et al.). Early partnerships are also critical to prioritize research goals and ensure that new CLC practices are deployed in scenarios with high likelihood of success (Mayerfeld et al.).

Conclusion

The articles in this Research Topic span a range of disciplines, describe several topics in agronomic and environmental quality research, and address several key factors for implementation: identifying and addressing research needs; shaping policy and program supports for CLC; and equipping the people and entities central to the transition. The Research Topic compiles research that represents current work and needs around CLC, but perhaps more importantly, it aims to define and establish the concept in the scientific literature. Although there are barriers to establishing CLC systems that are practically and economically viable and accessible to all farmers, CLC strategies offer a pathway to mitigate and perhaps avoid some of the worst harms caused by the dominant agricultural system in the U.S. Upper Midwest. Exciting opportunities are emerging in current research and through innovative partnerships. Pairing new science with an openness to learning more from historical and Indigenous approaches, CLC holds promise to create an agriculture that supports resilient farms, ecosystems, and rural communities.

Author contributions

ER: Conceptualization, Project administration, Writing – original draft, Writing – review & editing. AC-A: Conceptualization, Project administration, Writing – original draft, Writing – review & editing. JF: Conceptualization, Project administration, Writing – original draft, Writing – review & editing. JJ: Conceptualization, Project administration, Writing – original draft, Writing – review & editing. EM:

Conceptualization, Project administration, Writing – original draft, Writing – review & editing. CW: Conceptualization, Project administration, Writing – original draft, Writing – review & editing.

Funding

The author(s) declare that no financial support was received for the research, authorship, and/or publication of this article.

Acknowledgments

The authors thank Green Lands Blue Waters for supporting this Research Topic.

Conflict of interest

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References

Acharya, B. S., Blanco-Canqui, H., Mitchell, R. B., Cruse, R., and Laird, D. (2019). Dedicated bioenergy crops and water erosion. *J. Env. Qual.* 48, 485–492. doi: 10.2134/jeq2018.10.0380

Basche, A., and DeLonge, M. (2017). The impact of continuous living cover on soil hydrologic properties: a meta-analysis. *Soil Sci. Soc. Am. J.* 81, 1179–1190. doi: 10.2136/sssaj2017.03.0077

Becker, A. E., Horowitz, L. S., Ruark, M. D., and Jackson, R. D. (2022). Surface-soil carbon stocks greater under well-managed grazed pasture than row crops. *Soil Sci. Soc. Am. J.* 86, 758–768. doi: 10.1002/saj2.20388

Begum, N., Qin, C., Ahanger, M. A., Raza, S., Khan, M. I., Ashraf, M., et al. (2019). Role of arbuscular mycorrhizal fungi in plant growth regulation: implications in abiotic stress tolerance. *Front. Plant Sci.* 10, 1068. doi: 10.3389/fpls.2019.01068

Berdeni, D., Turner, A., Grayson, R. P., Llanos, J., Holden, J., Firbank, L. G., et al. (2021). Soil quality regeneration by grass-clover leys in arable rotations compared to permanent grassland: effects on wheat yield and resilience to drought and flooding. *Soil Till. Res.* 212, 105037. doi: 10.1016/j.still.2021.105037

Blake, S. F. (1939). A new variety of Iva ciliata from Indian rock shelter in the south-central United States. *Rhodora* 41, 81–86.

Boody, G., and DeVore, B. (2006). Redesigning agriculture. *Bioscience* 56, 839. doi: 10.1641/0006-3568(2006)56(839:RA)2.0.CO;2

Boody, G., Vondracek, B., Andow, D. A., Krinke, M., Westra, J., Zimmerman, J., et al. (2005). Multifunctional agriculture in the United States. *Bioscience* 55, 27. doi: 10.1641/0006-3568(2005)055(0027:MAITUS)2.0.CO;2

Carlisle, L. (2022). *Healing Grounds: Climate, Justice, and the Deep Roots of Regenerative Farming*. Washingto, DC: Island Press.

Chami, B., Niles, M. T., Parry, S., Mirsky, S. B., Ackroyd, V. J., and Ryan, M. R. (2023). Incentive programs promote cover crop adoption in the northeastern United States. *Agric. Env. Lett.* 8, e20114. doi: 10.1002/ael2.20114

Chrisman, S., Cureton, C., Hayden, D., Iutzi, F., Meier, E., Moore, E. B., et al. (2021). *Our Journey to a Transformed Agriculture through Continuous Living Cover*. Green Lands Blue Waters. Available online at: https://greenlandsbluewaters.org/wp-content/uploads/2021/08/OurJourneyToTransformedAgThruCLC-GLBW2021.pdf (accessed September 18, 2023).

Congressional Research Service (2021). *Racial Equity in U.S. Farming: Background in Brief. Congressional Research Service.* Available online at: https://crsreports.congress.gov/product/pdf/R/R46969 (accessed September 30).

Costa, O. Y. A., Raaijmakers, J. M., and Kuramae, E. E. (2018). Microbial extracellular polymeric substances: ecological function and impact on soil aggregation. *Front. Microbiol.* 9, 1636. doi: 10.3389/fmicb.2018.01636

Davis, A. S., Hill, J. D., Chase, C. A., Johanns, A. M., and Liebman, M. (2012). Increasing cropping system diversity balances productivity, profitability and environmental health. *PLoS ONE* 7, e47149. doi: 10.1371/journal.pone.0047149

Dennis, P. G., Miller, A. J., and Hirsch, P. R. (2010). Are root exudates more important than other sources of rhizodeposits in structuring rhizosphere bacterial communities?: Root exudates and rhizosphere bacteria. *FEMS Microbiol. Ecol.* 72, 313–327. doi: 10.1111/j.1574-6941.2010.00860.x

EWG (2023). *Total Commodity Programs, United States*. Washington, DC: Environmental Working Group. Available online at: https://farm.ewg.org/progdetail.php?fips=00000&progcode=totalfarm&regionname=theUnitedStates (accessed September 30).

Feyereisen, G. W., Wilson, B. N., Sands, G. R., Strock, J. S., and Porter, P. M. (2006). Potential for a rye cover crop to reduce nitrate loss in southwestern Minnesota. *Agron. J.* 98, 1416–1426. doi: 10.2134/agronj2005.0134

Franco, J. G., Berti, M. T., Grabber, J. H., Hendrickson, J. R., Nieman, C. C., Pinto, P., et al. (2021a). Ecological intensification of food production by integrating forages. *Agronomy* 11, 2580. doi: 10.3390/agronomy11122580

Franco, J. G., Duke, S. E., Hendrickson, J. R., Liebig, M. A., Archer, D. W., and Tanaka, D. L. (2018). Spring wheat yields following perennial forages in a semiarid no-till cropping system. *Agron. J.* 110, 2408–2416. doi: 10.2134/agronj2018.01.0072

Franco, J. G., Gramig, G. G., Beamer, K. P., and Hendrickson, J. R. (2021b). Cover crop mixtures enhance stability but not productivity in a semi-arid climate. *Agron. J.* 113, 2664–2680. doi: 10.1002/agj2.20695

Franco, J. G., King, S. R., Masabni, J. G., and Volder, A. (2015). Plant functional diversity improves short-term yields in a low-input intercropping system. *Agric. Ecosyst. Environ.* 203, 1–10doi: 10.1016/j.agee.2015.01.018

Hatfield, J. L., and Dold, C. (2017). "Climate variability effects on agriculture land use and soil services," in *Soil Health and Intensification of Agroecosytems*, eds M. M. Al-Kaisi, and B. Lowery (London: Academic Press), 25–50.

Hooper, D. U., Chapin, F. S., Ewel, J. J., Hector, A., Inchausti, P., Lavorel, S., et al. (2005). Effects of biodiversity on ecosystem functioning: a consensus of current knowledge. *Ecol. Monogr.* 75, 3–35. doi: 10.1890/04-0922

Isbell, F., Adler, P. R., Eisenhauer, N., Fornara, D., Kimmel, K., Kremen, C., et al. (2017). Benefits of increasing plant diversity in sustainable agroecosystems. *J. Ecol.* 105, 871–879. doi: 10.1111/1365-2745.12789

Jewett, J. G., and Schroeder, S. (2015). *Continuous Living Cover Manual*. Green Lands Blue Waters. Available online at: https://greenlandsbluewaters.org/wp-content/uploads/2019/08/CLC_Manual_FULL-1.pdf (accessed September 15, 2023).

Jordan, N., Boody, G., Broussard, W., Glover, J. D., Keeney, D., McCown, B. H., et al. (2007). Sustainable development of the agricultural bio-economy. *Science* 316, 1570–1571. doi: 10.1126/science.1141700

Jordan, N., and Warner, K. D. (2010). Enhancing the multifunctionality of US agriculture. *Bioscience* 60, 60–66. doi: 10.1525/bio.2010.60.1.10

Jordan, N. R., Dorn, K., Runck, B., Ewing, P., Williams, A., Anderson, K. A., et al. (2016). Sustainable commercialization of new crops for the agricultural bioeconomy. *Elementa* 4, 000081. doi: 10.12952/journal.elementa.000081

Jungers, J. M., DeHaan, L. H., Mulla, D. J., Sheaffer, C. C., and Wyse, D. L. (2019). Reduced nitrate leaching in a perennial grain crop compared to maize in the Upper Midwest, USA. *Agric. Ecosyst. Environ.* 272, 63–73. doi: 10.1016/j.agee.2018.11.007

Kahlon, M. S., Lal, R., and Ann-Varughese, M. (2013). Twenty two years of tillage and mulching impacts on soil physical characteristics and carbon sequestration in Central Ohio. *Soil Till. Res.* 126, 151–158. doi: 10.1016/j.still.2012.08.001

Kapayou, D. G., Herrighty, E. M., Hill, C. G., Camacho, V. C., Nair, A., Winham, D. M., et al. (2023). Reuniting the three sisters: collaborative science with Native growers to improve soil and community health. *Agric. Hum. Values* 40, 65–82. doi: 10.1007/s10460-022-10336-z

Kaspar, T. C., and Singer, J. W. (2011). *The Use of Cover Crops to Manage Soil*. Lincoln, OR: USDA ARS/UNL Faculty.

Kelly, C., Haddix, M. L., Byrne, P. F., Cotrufo, M. F., Schipanski, M., Kallenbach, C. M., et al. (2022). Divergent belowground carbon allocation patterns of winter wheat shape rhizosphere microbial communities and nitrogen cycling activities. *Soil Biol. Biochem.* 165, 108518. doi: 10.1016/j.soilbio.2021.108518

Khan, Q. A., and McVay, K. A. (2019). Productivity and stability of multi-species cover crop mixtures in the Northern Great Plains. *Agron. J.* 111, 1817–1827. doi: 10.2134/agronj2018.03.0173

Knapp, J., and Sciarretta, A. (2023). Agroecology: protecting, restoring, and promoting biodiversity. *BMC Ecol. Evol.* 23, s12862-023-02140-y. doi: 10.1186/s12862-023-02140-y

Lal, R. (2020). Soil organic matter and water retention. *Agron. J.* 112, 3265–3277. doi: 10.1002/agj2.20282

Lewandowski, S. (1987). Diohe'ko, the three sisters in seneca life: implications for a native agriculture in the finger lakes region of New York State. *Agric. Hum. Values* 4, 76–93. doi: 10.1007/BF01530644

Liebig, M. A., Hendrickson, J. R., Franco, J. G., Archer, D. W., Nichols, K., and Tanaka, D. L. (2018). Near-surface soil property responses to forage production in a semiarid region. *Soil Sci. Soc. Am. J.* 82, 223–230. doi: 10.2136/sssaj2017.07.0237

Liebman, M., and Schulte, L. A. (2015). Enhancing agroecosystem performance and resilience through increased diversification of landscapes and cropping systems. *Elementa* 3, 000041. doi: 10.12952/journal.elementa.000041

Loreau, M., Naeem, S., Inchausti, P., Bengtsson, J., Grime, J. P., Hector, A., et al. (2001). Biodiversity and ecosystem functioning: current knowledge and future challenges. *Science* 294, 804–808. doi: 10.1126/science.1064088

Mackail, J. W. (1950). *Virgil's Works: The Aeneid, Eclogues, Georgics.* New Yorkm NY: The Modern Library, 297.

Mathew, R. P., Feng, Y., Githinji, L., Ankumah, R., and Balkcom, K. S. (2012). Impact of no-tillage and conventional tillage systems on soil microbial communities. *Appl. Environ. Soil Sci.* 2012, 1–10. doi: 10.1155/2012/548620

Mayer, S., Wiesmeier, M., Sakamoto, E., Hübner, R., Cardinael, R., Kühnel, A., et al. (2022). Soil organic carbon sequestration in temperate agroforestry systems – A meta-analysis. *Agric. Ecosyst. Environ.* 323, 107689. doi: 10.1016/j.agee.2021.107689

McDaniel, M. D., Tiemann, L. K., and Grandy, A. S. (2014). Does agricultural crop diversity enhance soil microbial biomass and organic matter dynamics? A meta-analysis. *Ecol. Appl.* 24, 560–570. doi: 10.1890/13-0616.1

Moore, E. B. (2023). Challenges and opportunities for cover crop mediated soil water use efficiency enhancements in temperate rain-fed cropping systems: a review. *Land* 12, 988. doi: 10.3390/land12050988

Moore, E. B., Wiedenhoeft, M. H., Kaspar, T. C., and Cambardella, C. A. (2014). Rye cover crop effects on soil quality in no-till corn silage-soybean cropping systems. *Soil Sci. Soc. Am. J.* 78, 968–976. doi: 10.2136/sssaj2013.09.0401

Mueller, N. G., White, A., and Szilagyi, P. (2019). Experimental cultivation of eastern north america's lost crops: insights into agricultural practice and yield potential. *J. Ethnobiol.* 39, 549. doi: 10.2993/0278-0771-39.4.549

Nabhan, G. P., Colunga-GarcíaMarín, P., and Zizumbo-Villarreal, D. (2022). Comparing wild and cultivated food plant richness between the arid american and the mesoamerican centers of diversity, as means to advance indigenous food sovereignty in the face of climate change. *Front. Sustain. Food Syst.* 6, 840619. doi: 10.3389/fsufs.2022.840619

Neumann, G. (2007). "Root exudates and nutrient cycling," in *Nutrient Cycling in Terrestrial Ecosystems*, eds P. Marschner, and Z. Rengel (Berlin: Springer Berlin Heidelberg), 123–157.

Nichols, V. A., Moore, E. B., Gailans, S., Kaspar, T. C., and Liebman, M. (2022). Site-specific effects of winter cover crops on soil water storage. *Agrosyst. Geosci. Environ.* 5, e20238. doi: 10.1002/agg2.20238

NRCS (2014). *NRCS Conservation Practice Standard Cover Crop (Code 340) – Cover Crop*. United States Department of Agriculture. Available online at: https://www.nrcs.usda.gov/sites/default/files/2022-09/Cover_Crop_340_CPS.pdf (accessed September 18).

NRCS (2019). *NRCS Cover Crop Termination Guidelines*. United States Department of Agriculture. Available online at: https://www.nrcs.usda.gov/sites/default/files/2022-09/Termination_Guidelines_Designed_6.28_10.24am_%28002%29.pdf

Plastina, A., Liu, F., Sawadgo, W., Miguez, F., and Carlson, S. (2018). Partial budgets for cover crops in Midwest row crop farming. *J. Am. Soc.* 90–106.

Quarrier, C. L., Kwang, J. S., Quirk, B. J., Thaler, E. A., and Larsen, I. J. (2023). Pre-agricultural soil erosion rates in the midwestern United States. *Geology* 51, 44–48. doi: 10.1130/G50667.1

Rabalais, N. N., and Turner, R. E. (2019). Gulf of Mexico hypoxia: past, present, and future. *Limnol. Oceanogr. Bull.* 28, 117–124. doi: 10.1002/lob.10351

RMA (2019). *Cover Crops and Federal Crop Insurance*. Risk Management Agency, United States Department of Agriculture. Available online at: https://www.rma.usda.gov/en/Fact-Sheets/National-Fact-Sheets/Cover-Crops-and-Crop-Insurance (accessed September 18).

Rossier, C., and Lake, F. (2014). *Indigenous traditional ecological knowledge in agroforestry. Agroforestry Notes, 44.* U.S. Department of Agriculture, United States Forest Service, National Agroforestry Center. Available online at: https://www.fs.usda.gov/nac/assets/documents/agroforestrynotes/an44g14.pdf (accessed October 2).

Salmón, E. (2012). *Eating the landscape: American Indian stories of food, identity, and resilience*. Tucson, AZ: University of Arizona Press.

Sanderman, J., Hengl, T., and Fiske, G. J. (2017). Soil carbon debt of 12,000 years of human land use. *Proc. Natl. Acad. Sci. U. S. A.* 114, 9575–9580. doi: 10.1073/pnas.1706103114

Sanford, G. R., Posner, J. L., Jackson, R. D., Kucharik, C. J., Hedtcke, J. L., and Lin, T.-L. (2012). Soil carbon lost from Mollisols of the North Central U.S.A. with 20 years of agricultural best management practices. *Agric. Ecosyst. Environ.* 162, 68–76. doi: 10.1016/j.agee.2012.08.011

SARE (2014). *Integrating Continuous Living Cover Into Farming Systems Through Professional Development*. College Park, MD: Sustainable Agriculture Research and Education Program, National Institute of Food and Agriculture, U.S. Department of Agriculture.

Sauer, T. J., Dold, C., Ashworth, A. J., Nieman, C. C., Hernandez-Ramirez, G., Philipp, D., et al. (2021). "Agroforestry practices for soil conservation and resilient agriculture," in *Agroforestry and Ecosystem Services*, eds R. P. Udawatta, and S. Jose (Cham: Springer International Publishing), 19–48.

Schulte, L. A., Asbjornsen, H., Liebman, M., and Crow, T. R. (2006). Agroecosystem restoration through strategic integration of perennials. *J. Soil Water Conserv.* 61, 164A—169A.

Sokol, N. W., Kuebbing Sara, E., Karlsen-Ayala, E., and Bradford, M. A. (2019). Evidence for the primacy of living root inputs, not root or shoot litter, in forming soil organic carbon. *New Phytol.* 221, 233–246. doi: 10.1111/nph.15361

Sprunger, C. D., Martin, T., and Mann, M. (2020). Systems with greater perenniality and crop diversity enhance soil biological health. *Agric. Environ. Lett.* 5, e20030. doi: 10.1002/ael2.20030

Tamburini, G., Bommarco, R., Wanger, T. C., Kremen, C., Van Der Heijden, M. G. A., Liebman, M., et al. (2020). Agricultural diversification promotes multiple ecosystem services without compromising yield. *Sci. Adv.* 6, eaba1715. doi: 10.1126/sciadv.aba1715

Thaler, E. A., Kwang, J. S., Quirk, B. J., Quarrier, C. L., and Larsen, I. J. (2022). Rates of historical anthropogenic soil erosion in the Midwestern United States. *Earth's Fut.* 10, e2021EF002396. doi: 10.1029/2021EF002396

Tilman, D., Isbell, F., and Cowles, J. M. (2014). Biodiversity and ecosystem functioning. *Ann. Rev. Ecol. Evol. Syst.* 45, 471–493. doi: 10.1146/annurev-ecolsys-120213-091917

Tilman, D., Knops, J., Wedin, D., Reich, P., Ritchie, M., and Siemann, E. (1997). The Influence of functional diversity and composition on ecosystem processes. *Science* 277, 1300–1302. doi: 10.1126/science.277.5330.1300

USDA (2019). *2017 Census of Agriculture: Summary and State Data*. United States Department of Agriculture. Available online at: www.nass.usda.gov/Publications/AgCensus/2017/Full_Report/Volume_1,_Chapter_1_US/usv1.pdf (accessed October 1).

Wang, Z. H., and Li, S. X. (2019). "Nitrate N loss by leaching and surface runoff in agricultural land: a global issue (a review)," in *Advances in Agronomy*, ed. D. L. Sparks (London: Elsevier), 159–217.

Williams, D. R., Clark, M., Buchanan, G. M., Ficetola, G. F., Rondinini, C., and Tilman, D. (2020). Proactive conservation to prevent habitat losses to agricultural expansion. *Nat. Sustain.* 4, 314–322. doi: 10.1038/s41893-020-00656-5

Zhang, M., Lu, Y., Heitman, J., Horton, R., and Ren, T. (2017). Temporal changes of soil water retention behavior as affected by wetting and drying following tillage. *Soil Sci. Soc. Am. J.* 81, 1288–1295. doi: 10.2136/sssaj2017.01.0038