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MINI REVIEW
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Soil Health and Biodiversity Is Driven by Intensity of Organic Farming in Canada

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Organic farming is continuing to expand in Canada, with close to 6,000 producers farming over 2% of all agricultural land. There is insufficient evidence, however, of a trend toward larger average farm size and increasing specialization by these organic farms. This mini-review postulates that a gradient of intensity of farm management exists within organic farming sectors in Canada, with respect to cropping diversity, and tillage and nutrient utilization, and this gradient of intensity is a key determinant of agroecological outcomes. This variation in management approach and intensity reflects producer's individual perspectives on organic farming principles and practices, irrespective of farm scale. By directly influencing farm crop and vegetative diversity and cover, and farm nutrient status and carbon cycling, management intensity determines soil carbon storage and flux, soil health and biodiversity agroecological and ecosystem services, plus farm agronomic resilience. Demographic trends and perspectives of new entrants in organic farming are encouraging signs of an increasingly inclusive and socio-ecologically complex Canadian organic farming sector, which recognizes the agroecological implications of intensity of organic farm management across all production sectors.

Keywords: organic farming, soil organic carbon, soil health, soil biota, nutrients, farm scale, management intensity, Canada

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INTRODUCTION

Organic farming in Canada has been increasing steadily. By 2017 1.3 million hectares were farmed organically, an increase of almost 50% since 2011, and equivalent to approximately 2.1% of Canadian agricultural land. There are an estimated 5,791 certified organic producers across Canada (COTA, 2018). Both the type of production sector and agroecosytem biophysical constraints within each region strongly influence organic farm size in Canada. However, while organic farming continues to expand in Canada, there is no evidence of a trend toward larger average organic farm size. Hall and Mykroydy (2001), in a rare study to examine "conventionalizaton" of organic farms in Canada, found no trend of increasing farm size or specialization among 259 organic vegetable, fruit or field crop farms in Ontario.

While organic farm scale in Canada may not be increasing are there other aspects of organic farm composition and management that may be determinants of agroecological outcomes? If we define intensity of farm management as a reduction in cropping diversity combined with increasing tillage and nutrient utilization and flow on farm (Postma-Blaauw et al., 2010) to what degree is there a range of intensity of production and farm management approach within organic farming in Canada.

For example, in Ontario, Roberts et al. (2008) showed that within long-term organic dairy farming there was a spectrum of farm management approach. Farms fell broadly into three groups, differing in importance placed on farm feed self-sufficiency and livestock grazing regime. Critically, the choice of farm management approach impacted farm livestock density per hectare, farm productivity, and whole farm nutrient status. Furthermore, although social factors were outside the scope of this research it was clear from engagement with the participating farmers that this spectrum in management intensity was substantially attributable to the individual producer's philosophical perspective and approach with respect to organic farming. If gradients of intensity of management are common across organic farming sectors, what are the implications and impacts of such gradients in terms of agroecological and ecosystem services?

While this review focuses on agronomic intensification in organic farming, the concept of diversification as meaning cultivating socio-ecological complexity is key also to supporting organic farming's broader social and ecological goals in Canada and globally. To what degree is Canadian organic farming acting as a model of civil commons supporting social, economic and environmental services central to sustainability including resiliency to the threats of biodiversity loss, climate change and food insecurity (Lynch et al., 2014; Petersen-Rockney et al., 2021)? While data is limited, it is encouraging to see demographic trends for engagement in organic farming in Canada that are likely to influence multifunctional socio-ecological outcomes. Organic farmers in Canada, on average, are younger and more likely to come from non-farm backgrounds (Willer and Lernoud, 2018) and organic farms are less likely to be operated exclusively by men (Bialais, 2020). Cranfield et al. (2010) found health and environmental concerns were a larger motivation than economic considerations driving conversion to organic farming in Canada. Also, in addition to advances in gender equality in farm ownership and management, the reliance on modes of knowledge production and sharing appear distinct in organic farming (Lynch et al., 2014). These demographic trends and expanded perspectives, and potential further broadening of inclusivity, will continue to cultivate the socio-ecological complexity of organic farming in Canada.

The following condensed review examines how agroecological outcomes with respect to soil organic carbon, soil health and soil biodiversity are influenced by intensity of organic farming, with emphasis on the Canadian context and literature.

SOIL ORGANIC CARBON AND SOIL HEALTH

Shorter crop rotations, especially when including low residue crops such as soybean or potato, leads to a decline in SOC stocks as found in more intensive farming systems in Eastern Canada (Nyiraneza et al., 2017; Perez-Guzman et al., 2021). More diverse or extended crop rotations are recommended in organic farming systems, to maintain and enhance SOC, although this practice on farm may vary with scale and intensity of the farm operation (Lynch et al., 2014a; Lynch, 2015). Diversifying cropping alone, however, may not enhance SOC. Various studies suggest maintaining SOC levels may not be guaranteed by longer rotations unless a period in perennial forages are included (Arcand and Congreves, 2018; Sprunger et al., 2020). In addition, added diversification, including cover crops, may be associated with increased tillage frequency and thus enhance carbon flux but not SOC storage in soil. On organic grain farms in the mid-west US, Sprunger et al. (2021) found tillage frequency increased with crop diversity, and reduced both soil health (mineralizable C) and SOC. Few (22%) of the farms studied, however, included perennials—positively associated with improved soil health, within their 4-year crop rotations. Crystal-Ornelas et al. (2021) concluded that the specific influence of crop rotation length and diversity within organic farming on farm SOC is under researched. In this latter meta-analysis, cover cropping on organic farms did not influence SOC.

In humid regions of Canada, zero-tillage cropping does not enhance SOC (Angers et al., 2017), thus the contribution of regionally appropriate combinations of BMPs to maintain and enhance SOC storage needs to be developed. Various long-term studies suggest that the loss of SOC due to tillage in organic cropping systems for weed control and/or cover crop incorporation is offset by the added amount of residue returned to soil resulting in a net maintenance of SOC (Lynch, 2014). In a recent meta-analysis of the influence of best management practices (BMPs) within organic farming on SOC, Crystal-Ornelas et al. (2021) found use of organic amendments had the greatest influence, increasing SOC by 24% compared to 14% on average gains in SOC associated with conservation tillage. In usually smaller scale organic horticulture systems rotation diversity is partially or fully replaced by organic amendment, such as compost and mulch, application to sustain SOC (Burkhard et al., 2009).

In Europe Krauss et al. (2022) found reductions in organic crop biomass of 8% under reduced tillage systems is likely offset by added weed contributions accounting for some of the gains in SOC found under reduced tillage.

While more persistent or stored SOC, protected from decomposition, is comprised mainly of microbial products (Cortrufo et al., 2019) the role of soil biota and its diversity in SOC stabilization is unresolved (Chenu et al., 2019). Rotation history and cover crops may induce changes in the soil microbial community that in turn stimulate the turnover of other newly added crop or cover crop residue (Barel et al., 2019). This suggests that the greater temporal vegetative diversity in organic farming systems enhances microbial processing of organic C through the soil ecosystem and associated soil health benefits (Lynch, 2014, 2015). However, and as discussed below, the intensity with respect to nutrient status of organic farms must also be sufficient to avoid negatively impacting the fundamental carbon processing capacity of the soil biota. In arid regions greater mycorrhizal association with plants, as often found under organic management, may enhance crop water use efficiency and productivity and thus carbon returned to soil (Bender et al., 2016).

The decomposition and mineralization by the soil biota of the added residue dynamics on organic farms (i.e., carbon flux rather than SOC stock alone) may be equally important in maintaining soil health and biodiversity (Lynch et al., 2012; Lynch, 2014). Soil organic carbon is the keystone element affecting soil health outcomes and both total SOC and labile SOC [particulate (POMc), permanganate oxidizable (POXc), mineralizable C] are key components and measures of soil health (Hurisso et al., 2016; Norris et al., 2020). In studies of drivers of soil health, SOC-related variables often best explain dataset variability and are found to be the more robust indicators, as found for POXc on organic farms in Ontario (Hargreaves et al., 2019). How does cropping intensity and diversification influence soil health? In Michigan, while clay content was a dominant driver of soil health, Tu et al. (2021) found that crop diversification, regardless of composition—i.e., forages or cover crops, increased soil mineralizable C and aggregate stability, supporting the concept of overall spatial and temporal vegetative diversification being a key consideration. While agronomic benefits from cover crops to the following organic cash crops have been demonstrated (Alam et al., 2016, 2018) their routine use varies with intensity of organic farm management. For organic farms weeds also may be a not insignificant contribution to the vegetative diversity benefiting soil health. Nelson et al. (2009) demonstrated how extended (5 year) and more diverse rotations on organic potato farms in Atlantic Canada allowed for recovery, after the high tillage and low residue input potato phase, of the soil microbial and earthworm population. The diverse (annual/perennial mixture) crop rotation also maintained both labile (POMc) and total SOC levels in soil. Marshall and Lynch (2018, 2020) showed how SOC and soil microbial biomass and macrofauna recovered from a cover crop tillage phase in a 4-year organic grain rotation. Interestingly, in a social study of Atlantic Canada farmers rational for adopting farm management BMPs associated with soil health, participating organic farmers were found to be motivated by a concern for soil ecology more than solely economic considerations i.e., enhancing soil health attributes specifically linked to crop productivity (Mann et al., 2021).

Does such maintenance of SOC and soil health hold true also for more intensive organic cash crop farms characterized by shorter and less diversified field crop rotations? In partnership with the Organic Federation of Canada, and funded through the Agriculture and Agrifood Canada Organic Science cluster program and in collaboration with Universite Laval, Dalhousie University PhD candidate Stephanie Lavergne is currently examining the dynamics of SOC, soil health, and earthworm abundance and species diversity on organic grain farms in Quebec that utilize 3 year rotations of corn-soybean-wheat rotations but that also integrate cover crops.

A NOTE ON PHOSPHORUS

Where reduced intensity with respect to nutrient supply leads over time to resource/nutrient poor systems, such as organic farming systems with long term negative farm level phosphorus balances, soil microbial carbon use efficiency appears to decline. This in turn may lead to priming (i.e., mineralization and decomposition) of native SOC (Arcand et al., 2017). While the often distinct soil phosphorus status on organic farms can lead to shifts in organic phosphorus forms and cycling and even adaptations by the soil microbial community with respect to related gene expression (Fraser et al., 2015; Schneider et al., 2016, 2017b) phosphorus limitations, if sufficiently severe, can also undermine cover crop and green manure productivity, and thus residue (carbon) return to soil (Thiessen Martens et al., 2019). This emphasizes that management of SOC in organic farming systems must consider the intricately linked issue of intensity with respect to farm nutrient status (or balance) which may be associated more with organic producer philosophical approach and intensity of farm operation than farm scale *per se*. Even occasional livestock feed or soil P inputs can make the difference between organic farm deficiencies and adequate P supply (Roberts et al., 2008; Fraser et al., 2019).

While the intensity of organic farming influences farm nutrient status and efficiency, and the relative role of microbially mediated soil phosphorus supply, regional recycling of phosphorus (such as in processed manures, municipal food waste composts, struvite) will necessarily be an increasing consideration for all agriculture (Schneider et al., 2019). Powers et al. (2019) mapped the global opportunities for recycling of P from livestock and urban sources to surrounding cropland. A critical question for organic agriculture is to what degree it supports increased nutrient diversification and recycling at multiple spatial scales (within and between farms, and between urban and rural areas) and contributes to closing nutrient and resource loops.

BIODIVERSITY AND SOIL BIOTA

While the abundance and diversity of component soil biota populations in agroecosystems are very dynamic and highly influenced by changing farm management regimes, maintaining and enhancing soil biodiversity broadly sustains agroecosystem multifunctionality (Bender et al., 2016; Gonzalez et al., 2020). In general, land-use intensification decreases the abundance and community diversity of soil biota and reduces their potential beneficial effects on plant performance (Yang et al., 2018). In a study across 34 farms in Atlantic Canada, of which 40% were organic farms, lower-intensity management practices (perennial forage, mixed annual-perennial cropping), manure application and low tillage were found to be linked to soil health (higher soil respiration and water-stable aggregates), plus greater soil fungi, mycorrhizae, and Gram negative bacteria (Mann et al., 2019). While forages play an important role in many organic farming systems, is crop diversity rather than enhanced vegetative diversity (including weeds) in organic farming the strongest driver in maintaining soil biota diversity? A recent study from across Europe (Garland et al., 2021), showed crop diversity alone over the prior 10 years had a minor effect, when compared to combined vegetative cover (combining cash crops, cover crops and periods in forage), on soil microbial diversity, multifunctionality and yields suggesting that maintaining higher spatial and temporal diversity of vegetation across organic farming systems is key. A global metanalyses by Lori et al. (2017) found organic farming systems had greater soil microbial biomass and linked enzyme activities than conventional systems attributable to crop rotations and use of organic amendments. Crystal-Ornelas et al. (2021) found BMP use on organic farms increased soil microbial biomass by 30% when compared to organic farms not practicing BMPs.

On long term organic dairy farms in Ontario, lower livestock stocking density and thus lower internal farm manure flows of N and P nutrients, resulted in greater legume composition of forages and yields matching adjacent conventional dairy farms. Retaining legume content in mixed forages (or green manures) confers agronomic and economic resilience as it provides a nitrogen buffer maintaining crop yield and quality and less dependence on applied N including from manure or other sources (Lynch et al., 2004). The greater legume content, and lower readily available soil P status, on organic dairy farms was also associated with greater forage legume root colonization by mycorrhizae (AMF) and a shift in AMF community composition, along with greater legume biological N_2 fixation (Schneider et al., 2015, 2017a). A fascinating recent study (Puy et al., 2021) has shown that plant phenotypic changes incurred by water availability and by parent plant AMF association, is transferred to the next generation of plants, thus conferring environmental stress resiliency across plant generations. One can speculate thus that enhanced crop resiliency to climate stresses often observed on organic farms is due to some degree to greater AMF and other beneficial plant-soil microbe interactions.

In terms of biodiversity more broadly, the benefits of organic farming with respect to plants, pollinators and birds have been documented but the complexity of the surrounding landscape will also influence outcomes. For specific ecosystem services provided, or availed of, by an organic farm, such as bird diversity and pollination, outcomes are modified by both land use intensity and the heterogeneity of the surrounding landscape, plus time since conversion to organic farming. Large data gaps exist, however, with respect to understudied organism groups and genetic diversity, the linkage to ecosystem services, and a more nuanced evaluation of the influence of intensity of management within each farming sector (Lynch et al., 2012; Rundlöf et al., 2016; Kirk and Lindsay, 2017; Happe et al., 2018).

Does ecological theory provide some guidance as to the likely relationship between farm scale and the linkage between biodiversity and ecosystem functioning? As farm scale increases, in theory the greater range of environments on farm, including soil and habitat types (e.g., fields margins, woodlands), adds more opportunity for ecological niches and should strengthen the linkage between biodiversity and ecosystem functioning (Gonzalez et al., 2020). An interesting question, then, is to what degree spatial scale and niche opportunity constraints on smaller organic farm operations are accommodated by greater temporal diversity, and does the converse also hold, is less temporal diversification needed on potentially more spatially diverse larger organic farms? Larger organic farms, however, may not retain a greater range of environments and habitats. Indeed, as trade-offs with respect to field size-mediated ecological vs. economic benefits are still largely ignored in both policy and research a reduction in relative non-crop area and consolidation of fields may be considered more likely on larger organic farms (Clough and Kirchweger, 2020). In Sweden, Belfrage et al. (2005) found that while the largest differences were between small organic and large conventional farms with respect to herbaceous plant, birds, and pollinator species, farm size within organic farms also influenced these outcomes.

CONCLUSION

This mini-review demonstrates that gradients of intensity of farm management, including cropping diversity, and tillage and nutrient utilization, exist both across and within organic cropping and livestock sectors in Canada. This gradient in management intensity is a key driver of agroecological outcomes with respect to soil organic carbon, soil health and biodiversity and crop resilience. Organic farming is continuing to expand in Canada with no evident trend of increasing farm size and specialization. Demographic trends and surveys of perspectives of new entrants to Canadian organic farming are documenting an increasingly socio-ecological complex Canadian organic farming sector. It is a sector that appears motivated to design and manage organic farms at a level of intensity that is productive while ensuring ecosystem services linked to soil carbon storage and flux, soil health and soil biodiversity are sustained.

AUTHOR CONTRIBUTIONS

The author confirms being the sole contributor of this work and has approved it for publication.

REFERENCES

Alam, M. Z., Lynch, D. H., Sharifi, M., Burton, D. L., and Hammermeister, A. (2016). The effect of green manure and organic amendments on potato yield, nitrogen uptake and soil mineral nitrogen. *Biol. Agric. Horticult.* 32, 221–236. doi: 10.1080/01448765.2015.1133319

Alam, M. Z., Lynch, D. H., Tremblay, G., Gillis-Madden, R., and Vanasse, A. (2018). Optimizing combining green manures and pelletized manure for organic spring wheat production. *Can. J. Soil Sci.* 98, 638–649. doi: 10.1139/cjss-2018-0049

Angers, D., Bolinder, M. A., Carter, M. R., and Gregorich, E. G., Drury, C.F.Liang, B.C. et al. (2017). Impact of tillage practices on organic carbon and nitrogen storage in cool, humid soils of eastern Canada. *Soil Tillage Res.* 41, 191–201. doi: 10.1016/S0167-1987(96)01100-2

Arcand, M., and Congreves, K.A. (2018). Alternative management improves soil health indices in intensive vegetable cropping systems: a review. *Front. Environ. Sci.* 6, 1–18. doi: 10.3389/fenvs.2018.00050

Arcand, M., Levy-Booth, D. J., and Helgason, B. L. (2017). Resource legacies of organic and conventional management differentiate soil microbial carbon use. *Front. Microbiol.* 8, 2293. doi: 10.3389/fmicb.2017.02293

Barel, J. M., Kuyper, T.W., Paul, J., de Boer, W., Cornelissen, J. H. C., and De Deyn, G. B. (2019). Winter cover crop legacy effects on litter decomposition act through litter quality and microbial community changes. *J. Appl. Ecol.* 56, 132–143. doi: 10.1111/1365-2664.13261

Belfrage, K., Björklund, J., and Salomonsson, L. (2005). The effects of farm size and organic farming on diversity of birds, pollinators, and plants in a Swedish Landscape. *AMBIO*. 34, 582–588. doi: 10.1579/0044-7447-34.8.582

Bender, S. F., Wagg, C., and van der Heijden, M. G. A. (2016). An underground revolution: Biodiversity and soil ecological engineering for agricultural sustainability. *Trends Ecol. Evol.* 31, 440–452. doi: 10.1016/j.tree.2016.02.016

Bialais, C. (2020). *Organic Agriculture in Canada. Publication N. 2020-07-E. Parliamentary Information and Research Service*. Ottawa, Canada: Library of Parliament.

Burkhard, N. E., Lynch, D. H., Percival, D. C., and Sharifi, M. (2009). Organic mulch impact on vegetation dynamics and productivity of highbush blueberry under organic production. *Hortscience* 44, 1–9. doi: 10.21273/HORTSCI.44.3.688

Chenu, C., Angers, D. A., Barré, P., Derrien, D., and Arrouays, D. B. (2019). Increasing organic stocks in agricultural soils: Knowledge gaps and potential innovations. *Soil Tillage Res.* 188, 41–52. doi: 10.1016/j.still.2018.04.011

Clough, Y., and Kirchweger, S. and Kantelhardt. (2020). Field sizes and the future of farmland biodiversity in European landscapes. *Conserv. Lett.* 13, e12752. doi: 10.1111/conl.12752

Cortrufo, M. F., Ranalli, M. G., Haddix, M. L., Six, J., and Lugato, E. (2019). Soil carbon storage informed by particulate and mineral-associated organic matter. *Nat. Geosci.* 12, 989–994. doi: 10.1038/s41561-019-0484-6

COTA (Canadian Organic Trade Association). (2018). *Organics in Canada. By the Numbers: 2018 Data*. Available online at: https://www.canada-organic.ca/en/what-we-do/data-research/production-data (accessed on November 8, 2021).

Cranfield, J., Henson, S., and Holliday, J. (2010). The motives, benefits, and problems of conversion to organic production. *Agric. Hum. Values*. 27, 291–306. doi: 10.1007/s10460-009-9222-9

Crystal-Ornelas, R. T., Thapa, R., and Tully, K.L. (2021). Soil organic carbon is affected by organic amendments, conservation tillage, and cover cropping in organic farming systems: a meta-analysis. *Aric. Ecosys. Envir.* 312, 107356. doi: 10.1016/j.agee.2021.107356

Fraser, T., Lynch, D. H., Entz, M. H., and Dunfield, K. E. (2015). Linking alkaline phosphatase activity with bacterial phoD gene abundance in soil from a long-term management trial. *Geoderma*. 257–258, 115–122. doi: 10.1016/j.geoderma.2014.10.016

Fraser, T. D., Lynch, D. H., and O'Halloran, I. P. V. (2019). Soil phosphorus bioavailability as influenced by long-term management and applied phosphorus source. *Can. J. Soil Sci*. 99, 292–304. doi: 10.1139/cjss-2018-0075

Garland, G., Edlinger, A., Banerjee, S., Degrune, F., García-Palacios, P., Pescador, D.S. et al. (2021). Crop cover is more important than rotational diversity for soil multifunctionality and cereal yields in European cropping systems. *Nat. Food* 2, 28–37. doi: 10.1038/s43016-020-00210-8

Gonzalez, A., Germain, R. M., Srivastava, D. S., Filotas, E., Dee, L. E., and Gravel, D. (2020). Scaling-up biodiversity-ecosystem functioning research. *Ecol. Lett.* 23, 757–776. doi: 10.1111/ele.13456

Hall, A., and Mykroydy, V. (2001). Organic farmers in Ontario: an examination of the conventionalization argument. *Sociologia Ruralis*. 41, 399–422. doi: 10.1111/1467-9523.00191

Happe, A., Riesch, F., Rösch, V., Gallé, R., Tscharntke, T., and Batáry, P. (2018). Small-scale agricultural landscapes and organic management support wild bee communities of cereal field boundaries. *Agric. Ecosyst. Environ.* 254, 92–98. doi: 10.1016/j.agee.2017.11.019

Hargreaves, S. K. DeJong, P., Laing, K., McQuail, T., and Van Eerd, L.L. (2019). Management sensitivity, repeatability and consistency of interpretation of soil health indicators on organic farms in southwestern Ontario. *Can. J. Soil Sci*. 12, 1–12. doi: 10.1139/cjss-2019-0062

Hurisso, T. T., Culman, S. W., Horwath, W. R., Wade, J., and Cass, D. J.W. et al. (2016). Comparison of permanganate-oxidizable carbon and mineralizable carbon for assessment of organic matter stabilization and mineralization. *Soil* Sci. *Soc. Amer. J.* 80, 1352–1364. doi: 10.2136/sssaj2016.04.0106

Kirk., D.A., and Lindsay, K.E.F. (2017). Subtle differences in birds detected between organic and nonorganic farms in Saskatchewan Prairie Parklands by farm pair and bird functional group. *Agric. Ecosyst. Environ.* 246, 184–201. doi: 10.1016/j.agee.2017.04.009

Krauss, M., Wiesmeier, M., Don, A., Cuperus, A., Gattinger, A., and Gruber, S. (2022). Reduced tillage in organic farming affects soil organic carbon stocks in temperate Europe. *Soil Tillage Res.* 105262 doi: 10.1016/j.still.2021.105262

Lori, M., Symnaczik, S., Mäder, P., De Deyn, G., and Gattinger, A. (2017). Organic farming enhances soil microbial abundance and activity—A meta-analysis and meta-regression. *PLOS ONE*. 12, e0180442. doi: 10.1371/journal.pone.0180442

Lynch, D.H.., Voroney, R.P., and Warman, P.R. (2004). Nitrogen availability from composts for humid region perennial grass and legume-grass forage production. *J. Enviro. Q.* 33, 1509–1520. doi: 10.2134/jeq2004.1509

Lynch, D. H. (2014). "Sustaining soil organic carbon, soil quality and soil health in organic field crop management systems," in *Managing Energy, Nutrients and Pests in Organic Field Crops*, eds R. C. Martin, and R. MacRae, R. (Boca Raton, Fl: CRC Press), 107–132

Lynch, D. H. (2015). Nutrient cycling and soil health in organic cropping systems - importance of management strategies and soil resilience. *Sustain. Agric. Res*. 4, 76–84. doi: 10.5539/sar.v4n3p80

Lynch, D. H., Halberg, N., and Bhatta, G. D. (2012). Environmental impacts of organic agriculture in temperate regions. *CAB Rev.* 7, 1–17. doi: 10.1079/PAVSNNR20127010

Lynch, D. H., Sumner, J., and Martin, R. C. (2014). "Transforming recognition of the social, ecological and economic goods and services derived from organic agriculture in the Canadian context," in *Organic Farming; Prototype for Sustainable Agricultures,* eds S. Bellon, and S, Penvern (New York, NY: Springer Science+Business Media), 347–366.

Mann, C., Lynch, D. H., Dukeshire, S., and Mills, A. (2021). Farmers' perspectives on soil health in Maritime Canada. *Agroecol. Sust. Food Systems*. 45, 673–688. doi: 10.1080/21683565.2020.1866143

Mann, C., Lynch, D. H., Fillmore, S., and Mills, A. (2019). Relationships between field management, soil health and microbial community composition. Appl. *Soil Ecol.* 144, 12–21. doi: 10.1016/j.apsoil.2019.06.012

Marshall, C. B., and Lynch, D. H. (2018). No-till green manure termination influences soil organic carbon distribution and dynamics. *Agron. J.* 110, 1–9. doi: 10.2134/agronj2018.01.0063

Marshall, C. B., and Lynch, D. H. (2020). Soil microbial and macrofauna dynamics under different green manure termination methods. Appl. *Soil Ecol.* 148, 103505. doi: 10.1016/j.apsoil.2020.103505

Nelson, K. L., Lynch, D. H., and Boiteau, G. (2009). Assessment of changes in soil health throughout organic potato rotation sequences. *Agric. Ecosys. Environ.* 131, 220–228. doi: 10.1016/j.agee.2009.01.014

Norris, C. E., Mac Bean, G., Cappellazzi, S. B., Cope, M., Greub, K. L. H., and Liptzin, D. (2020). Introducing the North American project to evaluate soil health measurements. *Agron. J.* 112, 3195–3215. doi: 10.1002/agj2.20234

Nyiraneza, J., Thompson, B., Geng, X., He, J., Jiang, Y., and Fillmore, S. (2017). Changes in soil organic matter over 18 yr in Prince Edward Island, Canada. *Can. J. Soil Sci.* 97, 745–756. doi: 10.1139/CJSS-2017-0033

Perez-Guzman, L., Phillips, L. A., Seuradge, B. J., Agomoh, I., Drury, C. F., and Acosta-Martínez, V. (2021). An evaluation of biological soil health indicators in four long-term continuous agroecosystems in Canada. Agroecosyst. *Geosci. Environ*. 4, e20164. doi: 10.1002/agg2.20164

Petersen-Rockney, M., Baur, P., Guzman, A., Bender, S. F., Calo, A., Castillo, F., et al. (2021). Narrow and brittle or broad and nimble? Comparing adaptive capacity in simplifying and diversifying farming systems. *Front. Sustain. Food Syst*. 5, 564900. doi: 10.3389/fsufs.2021.564900

Postma-Blaauw, M., de Goede, R. G. M., Bloem, J., Faber, J. H., and Brussaard, L. (2010). Soil biota community structure and abundance under agricultural intensification and extensification. *Ecology*. 91, 460473. doi: 10.1890/09-0666.1

Powers, S. M., and Chowdury, R. B., MacDonald, G.K., Metson, G.S., Beusen, SA.H.W., Bouwan, S.E. et al. (2019). Global opportunities to increase agricultural independence through phosphorus recycling. *Earth's Future*. 7, 370–383. doi: 10.1029/2018EF001097

Puy, J., Carmona, C.P., Hiiesalu, I., Öpik, M., de Bello, F., and Moora, M. (2021). Mycorrhizal symbiosis alleviates plant water deficit within and across generations via plant plasticity. *J. Ecol.* 1:2020-07 doi: 10.1101/2020.07.21.213421

Roberts, C. J., Lynch, D. H., Voroney, R. P., Martin, R. C., and Juurlink, S. D. (2008). Nutrient budgets of Ontario organic dairy farms. *Can. J. Soil Sci.* 88, 107–114. doi: 10.4141/S06-056

Rundlöf, M., Henrik G Smith, H.G., and Birkhofer, K. (2016). Effects of organic farming on biodiversity. In: *eLS*. Chichester, England: John Wiley and Sons, Ltd.

Schneider, K., Lynch, D., Bünemann, E. K., and Voroney, P. (2017a). Vegetative composition, AMF root colonization, and biological N fixation distinguish organic and conventional perennial forage systems. *Agron. J.* 109, 1697–1706. doi: 10.2134/agronj2016.12.0700

Schneider, K. D., Cade-Menun, B., Lynch, D. H., and Voroney, R. P. (2016). Soil phosphorus forms from organic and conventional forage fields. *SSSAJ*. 80, 328–340. doi: 10.2136/sssaj2015.09.0340

Schneider, K. D., Lynch, D. H., Dunfield, K., Khosla, K., Jansa, J., and Voroney, R. P. (2015). Farm system management affects community structure of arbuscular mycorrhizal fungi. *Appl. Soil Ecol.* 96, 192–200. doi: 10.1016/j.apsoil.2015.07.015

Schneider, K. D., Thiessen Martens,J. R., Zvomuya, F., Reid, D. K., Fraser, T. D., and Lynch, D.H., et al. (2019). Options for improved phosphorus cycling and use in agriculture at the field and regional scales. *J. Env. Qual.* 48, 1247–1264. doi: 10.2134/jeq2019.02.0070

Schneider, K. D., Voroney, R. P., Lynch, D. H., Oberson, A., Frossard, E., and Bünemann, E. K. (2017b). Microbially-mediated P fluxes in calcareous soils as a function of water-extractable P. *Soil Biol. Biochem.* 106, 51–60. doi: 10.1016/j.soilbio.2016.12.016

Sprunger, C. D., Culman, S. W., Deiss, L., Brock, C., and Jackson-Smith, D. (2021). Which management practices influence soil health in Midwest organic corn systems. *Agron. J.* 113, 4201–4219. doi: 10.1002/agj2.20786

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

Thiessen Martens, J., and Lynch, R. D.H., and Entz, M. (2019). A survey of green manure productivity on dryland organic grain farms in the eastern prairie region of Canada. *Can. J. Plant Sci.* 99, 772–776. doi: 10.1139/cjps-2018-0311

Tu, X. DeDecker, J., Viens, F., and Snapp, S. (2021). Environmental and management drivers of soil health indicators on Michigan field crop farms. *Soil Tillage Res.* 213, 105146. doi: 10.1016/j.still.2021.105146

Willer, H., and Lernoud, J. (Eds.) (2018). *The World of Organic Agriculture. Statistics and Emerging Trends 2018.* Bonn, Germany: Research Institute of Organic Agriculture (FiBL), Frick, and IFOAM—Organics International.

Yang, G., Wagg, C., Veresoglou, S. D., Hempel, S., and Rillig, M. C. (2018). How soil biota drive ecosystem stability. *Trends Plant Sci.* 23, 1057–1067. doi: 10.1016/j.tplants.2018.09.007

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