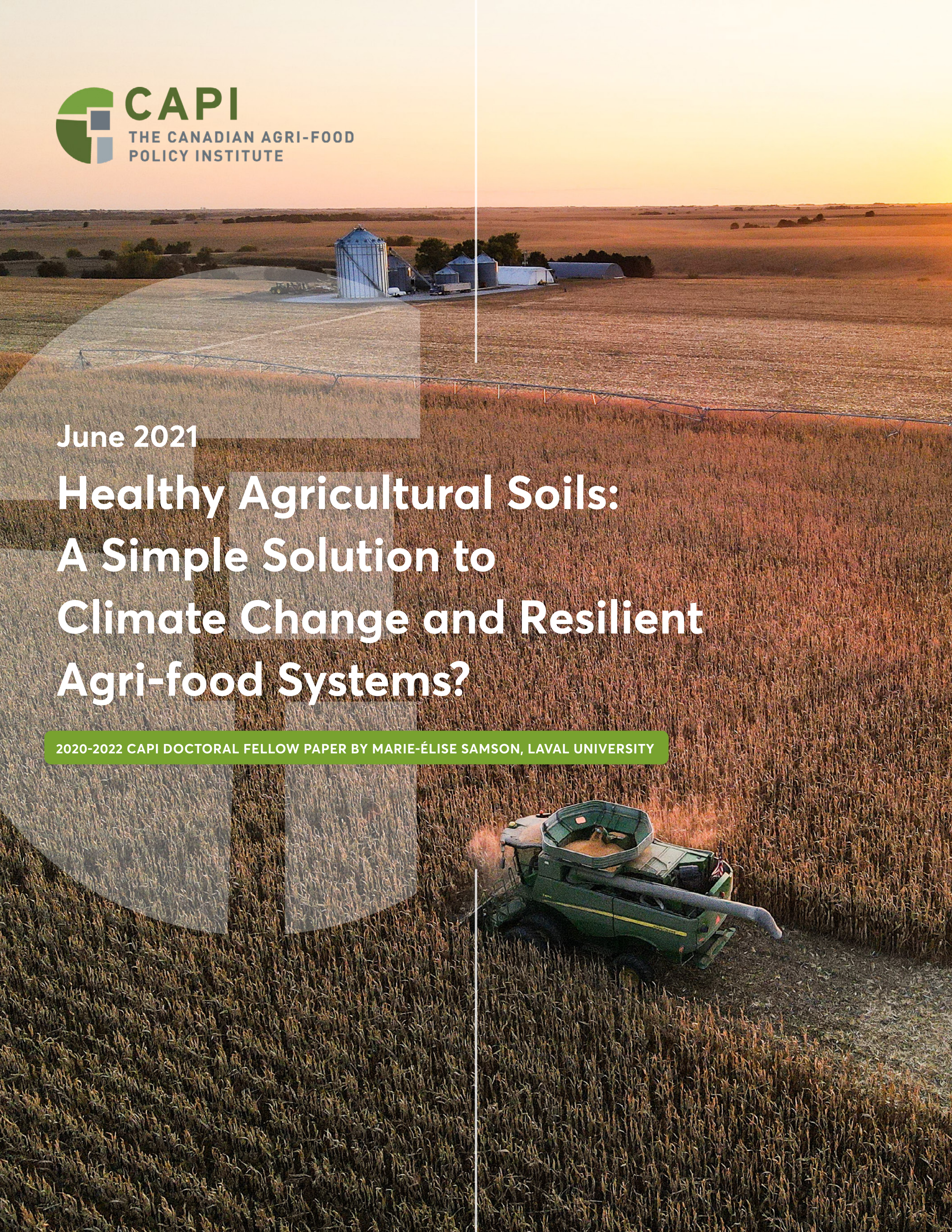

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Healthy Agricultural Soils: A Simple Solution to Climate Change and Resilient Agri-food Systems?

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Abstract

Adopting soil conservation practices in agriculture could help ensure the long-term productivity of our land and increase the resilience of our agricultural systems, while helping mitigate climate change by promoting soil carbon sequestration in soil. However, one question remains: are soil conservation practices a silver bullet, or are there any trade-offs between yield, soil health and carbon storage in soil? The objective of this project was to compare crops yield (corn, soybean, wheat) and environmental impact (soil health and soil carbon storage) of 20 different combinations of management practices including tillage regime (minimum tillage, mouldboard plowing), crop residue management (harvested or returned to soil) and five different fertilizer sources (organic and mineral) on two soils with contrasting textures (sandy loam and silty clay) over a nine-year period in eastern Canada. The results of this study highlighted the fact that the optimization of crop yields, soil health, and soil carbon sequestration do not always go hand in hand and that soil agronomic and environmental services can be greatly influenced by interactions between management practices and/or the pedoclimatic context. Furthermore, the results of this study demonstrated that, although generally overlooked in the measurement and reporting of soil carbon stocks, subsoil (> 30 cm) carbon can be very reactive to certain agricultural management practices and should be systematically considered in soil-based mitigation and adaptation strategies. These results are a call to recognize the inherent complexity of agro-ecosystems and to invest in the development of reliable tools for measuring and predicting the effect of management practices on soil health and soil carbon stock changes. They are also a call to recognize the true value of all the ecosystem services provided by agricultural soils. Although crop yields and the profitability of the farm are currently the main factors driving the market and decision-making, countries that manage to invest in the sustainability of their agri-food systems will necessarily benefit over the long term. If it can recognize that value, Canada can invest in the resilience of its agri-food system and will be able to rely on a return on its investment in the years to come.

Introduction

Organic matter in soils is considered one of the main indicators of soil health. Soil rich in organic matter is usually more productive and resilient. However, since the advent of intensive farming, it is estimated that soils have lost between 20% and 70% of their initial organic content worldwide. In parallel, there has been decline in productivity on roughly 20% of the arable land. The overall nature of these issues threatens our ability to ensure food security for future generations. Fortunately, adopting soil conservation practices in agriculture could help reverse these trends. Since these practices typically enhance soil organic matter content, they may not only help ensure the long-term productivity of our land (Oldfield et al., 2019) and increase the resilience of our agricultural systems (UNCCD, 2017), but also help mitigate climate change by promoting soil carbon sequestration (Figure 1). In fact, adopting simple conservation practices, such as reduced tillage and returning crop residues to the soil could enable 2 to 3 GT of carbon per year to be stored in agricultural soils as organic matter, thereby offsetting 20% to 35% of the world's anthropogenic greenhouse gas emissions (Minasny et al. 2017).

At the Conference of the Parties in Paris (Paris Agreement) in December 2015, Canada set ambitious targets by committing to reducing its greenhouse gas (GHG) emissions by 30% (compared with the 2005 levels), by 2030. By adopting certain soil conservation practices, Canadian agricultural producers could thus contribute to Canada's targets as well as increase the resilience of their farms (water management, nutrient management, etc.), which would better meet the sector's urgent needs for adapting to climate change, and thereby help ensure the sustainability of the Canadian agri-food system.

However, optimizing crop yields, soil health, and soil carbon sequestration do not always go hand in hand. In fact, the climate, soil type, and interactions among the various farming practices can significantly impact the net effect of these practices, and thus soil ecosystem services (Lal et al. 2011). Developing agricultural strategies that are effective both agronomically and environmentally therefore requires taking a holistic and systemic approach to the agro-ecosystem.

In Canada, for example, the widespread adoption of direct seeding in the prairie provinces has improved yields, soil quality, and soil carbon storage due to relatively dry climatic conditions. However, in Eastern Canada's colder and wetter conditions, direct seeding can sometimes reduce yields (Pittlekow et al. 2015) and generally has no impact on total soil carbon stocks (Angers and Eriksen-Hamel 2008). To date, the edaphic processes underlying these differences are still poorly understood. Therefore, developing an integrated understanding of agricultural systems and the physical and biogeochemical mechanisms underlying them is necessary for identifying the combinations of practices to be favoured under different pedoclimatic and growing conditions. The purpose of this study was to examine the effect of combining different soil conservation practices on corn, wheat and soybean crop yields, on soil health and fertility, and on soil carbon stocks in Eastern Canada's pedoclimatic context.

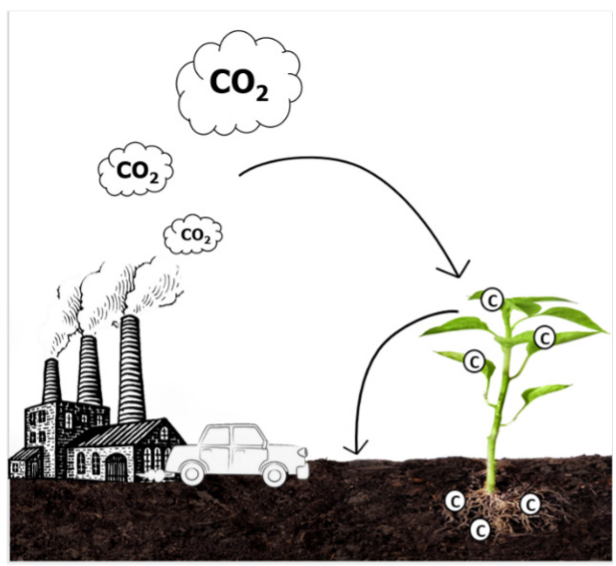

Figure 1. CO2 released into the atmosphere can be captured by plants and converted into plant-based organic matter through photosynthesis. The carbon contained in plant-based organic matter can then be returned to the soil and stabilized there over the long term via fine organo-mineral associations.

Methodology

This research project is based on a long-term trial located at the Université Laval's agricultural research station in St-Augustin-de-Desmaures, near Quebec City, Canada. The arrangement was set up in fall 2008 and is thoroughly described in Samson et al. (2019). It is replicated on a silty clay and a sandy loam soil. Each experimental site is a split-split-plot factorial design consisting of three repetitions in complete blocks and combining various tillage regimes (reduced tillage in spring vs. fall ploughing and spring reduced tillage), crop residue management (residues harvested vs. left on the soil) and five different fertilizer sources (poultry manure, cattle manure, hog manure, complete mineral fertilizer (NPK), and nitrogen-free mineral fertilizer (PK)). This experimental structure makes it possible to assess not only the net impact of each practice, but also determine whether there are interactions between each of these practices. Both sites grew wheat in 2009 and 2010, followed by a corn/soybean/wheat rotation from 2010 to 2017 (one crop per growing season). This experimental design, unique in the world, made it possible to assess the agronomic and environmental impact of 20 different cropping systems on two contrasting-texture Brunisols over a nine-year period. The yields of the corn, wheat and soybean crops were evaluated between 2009 and 2017. After each harvest, surface soil samples were collected (0-10 cm) to assess the changes in various soil health indicators (organic carbon concentration, microbial biomass, weighted mean diameter of the aggregates, etc.). Biochemical analyses of the soil organic matter, conducted in 2015, enabled us to better understand the impact of various farming practices on the quality of the organic matter at the surface and on its potential role in carbon storage and/or soil fertility. Lastly, in 2016, the total soil organic carbon stocks were measured to a depth of 60 cm in order to assess each technical itinerary's potential for soil carbon storage.

Results

Does no-till always yield more?

Reduced tillage is presented as the main pillar of soil conservation practices in field crops production. Its beneficial effects on biological, chemical and physical properties of the surface soil are well established (Hobbs et al. 2008) and sometimes even has a positive effect on crop yields, especially in dry climates where water availability is one of the main factors limiting crop yields (Ogle et al. 2012). However, our results (Samson et al., 2019), like those of other researchers, (Toliver et al., 2012; Pittelkow et al., 2015) showed that in cold, wet conditions, reduced tillage's impact on yield may be more variable. For example, in our silty clay soil, reduced tillage resulted in higher average grain yields (8% to 30%) than those of ploughing for all crops, but only after a 6-year transition period (Figure 2). In sandy loam, however, the impact of reduced tillage on yield depended primarily on the plant species grown; it had a beneficial effect on soybean yield, little effect on wheat yield, and a negative effect on corn yield (Figure 1). Yet, the negative impact of reduced tillage on corn yield was observed only when that practice was combined with returning the wheat crop residues to the soil, probably because of a mulch effect which could have delayed emergence and/or have led to nitrogen immobilization. Corn being a particularly demanding plant in terms of heat and nitrogen (Tremblay et al. 2012) probably explains why the negative impact of this interaction on yield was observed only for this crop and not for wheat and soybeans.

In addition to residues accumulating on the soil surface, reduced tillage can also impact yields by adding complexity to weed control, especially for perennial adventive species (Brainard et al. 2013). In our trial, we observed a greater prevalence of yellow foxtail in the sandy loam when the corn plots were grown using reduced tillage. Managing adventive species is a well-known issue among producers who have adopted reduced tillage techniques (Brainard et al. 2013). Due to the absence of mechanical breakdown of adventive roots systems with ploughing, reduced tillage is often accompanied by increased herbicide use (Day et al. 1999). Among other things, this issue means that the benefits of reduced tillage for the environment are sometimes debated (Lankoski et al. 2006). Hence, a growing number of researchers and producers are interested in using intercropping and/or cover crops to improve weed control in reduced tillage systems, or direct seeding (Mirsky et al. 2012; Masilionyte et al. 2017). However, this integrated management strategy requires developing a well-thought-out crop plan in order to prevent those species from becoming a pathogen infection site for the main crops and/or competing with them for water and nutrients (Mirsky et al. 2012). In practice, though, small reductions in yield can be accepted by producers using direct seeding or reduced tillage due to the lower production costs (Soane et al. 2012). However, to ensure a successful transition, adopting reduced tillage should ideally be overseen by professionals, in order to best adapt the application of this practice, factoring in the operation's pedoclimatic and cropping specifics.

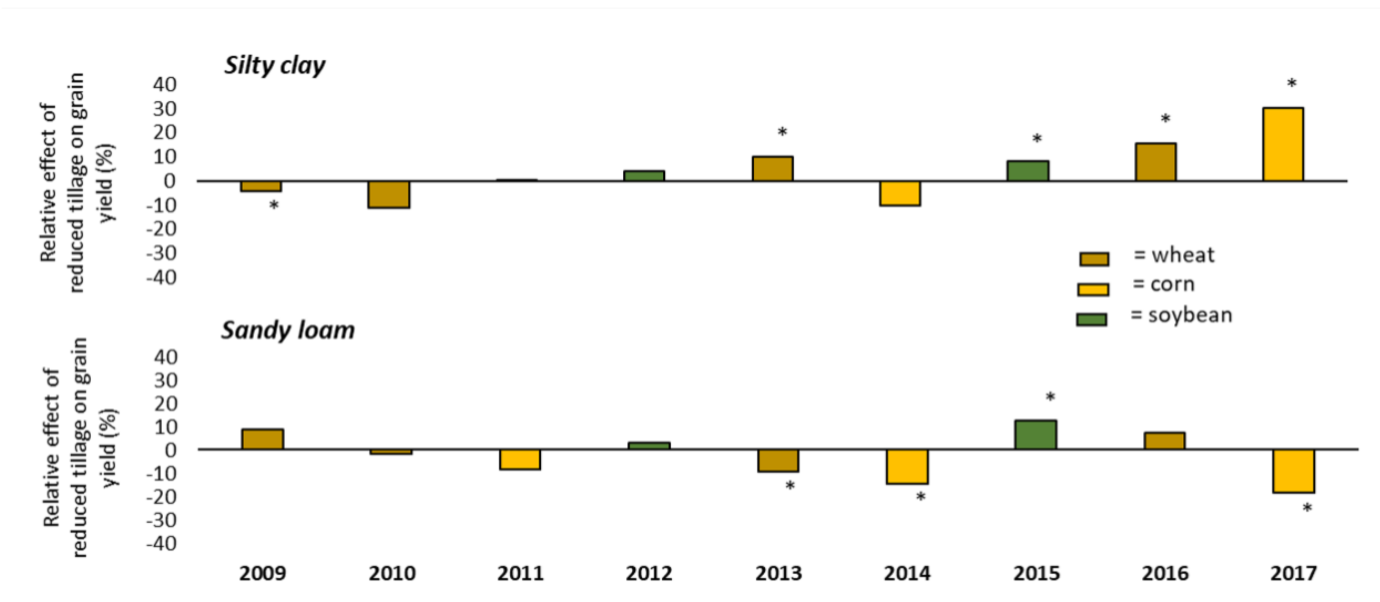

Figure 2. Yield gains or losses (%) with reduced tillage, when compared to ploughing, depending on soil type, year, and crop. The asterisk indicates statistically significant differences.

Potential for manures as fertilizers?

In this trial, mineral fertilizer (NPK) was often associated with higher yields for corn (Figure 3) and sometimes also for wheat. However, yields with farm manures were always substantially higher than those obtained with the nitrogen-free mineral control (PK). One of the strengths of this design was that it made it possible to compare, under the same pedoclimatic conditions, the use of three different farm manures with contrasting biochemical properties. Among the farm manures studied, liquid swine manure was the one that usually led to the best yields, probably due to its low C/N ratio and high NH4-N concentration (Webb et al., 2013). However, when liquid farm manures, such as liquid dairy and swine manures, were combined with returning residues to the silty clay soil, a decrease in corn yields was observed. This effect was not seen when residue return was combined with solid fertilizers (mineral fertilizers and poultry manure). It is therefore likely that the large amount of wheat residues left on the ground the previous year absorbed the liquid fertilizers, making the nutrients less available for the plants during critical crop growth phases.

The effectiveness of the various fertilizer sources was also closely associated with the climatic conditions during the growing season, especially for the corn. While the mineral fertilizer enabled acceptable corn yields (VS average of 7 072 kg/ha for the region), regardless of the year, the yield for the corn fertilized with farm manures depended on the climatic conditions during the growing season (Figure 3). In 2011, for example, the conditions were favorable to the mineralization of the soil organic matter and of farm manures, and the yield difference between the farm manures and mineral fertilizers was relatively small, even non-existent for the swine manure. However, in 2017, the very dry conditions during corn pollination likely had a negative impact on the mineralization of organic nitrogen in farm manures and the soil. Under those conditions, yields were on average 38% lower with farm manures than with complete mineral fertilizers and up to 73% lower with the control than with mineral fertilizer.

Yields were also generally more sensitive to the fertilizer source (mineral or organic) in the sandy loam than in the silty clay soil. Due to its higher initial content of organic matter, the soil more readily

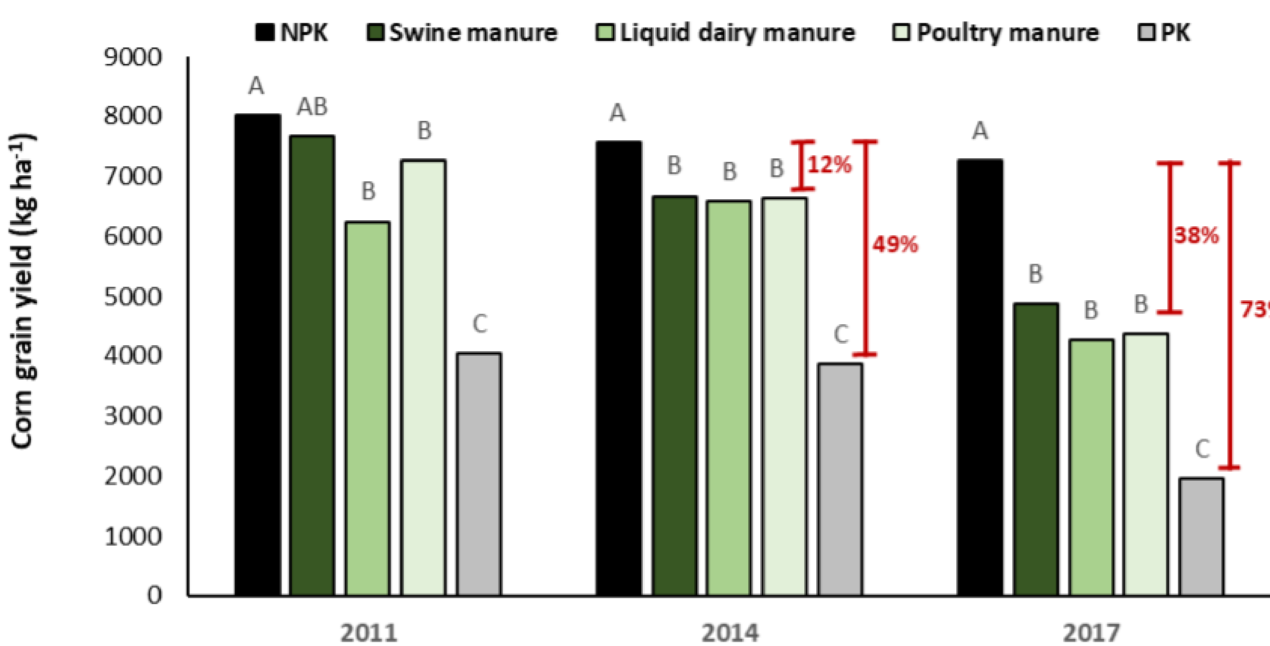

Figure 3. Graphical representation of the impact of the growing year on the average (both soils and all othe management practices combined) grain corn yield obtained with various fertilizer sources.

provides the nutrients needed for the plants in silty clay; whereas in sandy loam, it depends more on the exogenous inputs of organic matter and nutrients (Bloom et al., 1988; Webb et al., 1998). In the sandy loam, having a potentially lower ability to provide nitrogen to the plant (Schipanski et al., 2010), the yield differences based on fertilizer source were higher, and a positive residual effect of the farm manures on soybean yield was also seen. That positive residual effect from the farm manures on soybean yield may have been the result of improved soil fertility after repeated application of these organic fertilizers (Nyiraneza et al. 2010; Webb et al. 2013) and/or due to better nodulation in those conditions (Ganeshamurthy et Sammi Reddy, 2000).

Since the yields with the farm manures were very acceptable for wheat (average of 3512 kg/ha VS average of 2 165 kg/ha for the region) and sometimes even had a positive residual effect on soybean yield (average of 3757 kg/ha VS average of 2 258 kg/ha for the region), it would probably be ideal to use farm manures with wheat, but to consider a complementary fertilization strategy for corn, given its very high nitrogen requirements. An interesting strategy would be to consider using a legume cover crop in the fall before corn is grown. In fact, legumes have the advantage of fixing atmospheric nitrogen in the soil while contributing a limited amount of phosphorus when returned to soil. A meta-analysis by Charles et al. (2017) highlighted an equivalent mineral nitrogen input of 86 kg N ha-1 and a yield gain of 16% to 27% when a legume cover crop was planted the year before a main corn crop. Also, when combined with the use of farm manures, cover crops have the advantage of improving nitrogen retention in the soil from farm manures and reducing the leaching of nutrients into the waterways (Parkin et al. 2006; Cambardella et al. 2010).

Conservation practices and soil health

In this study, soil conservation practices (reduced tillage, returning crop residues to the soil, and using farm manures) generally helped improve the surface soil health indicators (0-10 cm), when compared with conventional practices or controls, regardless of soil type (Figure 4).

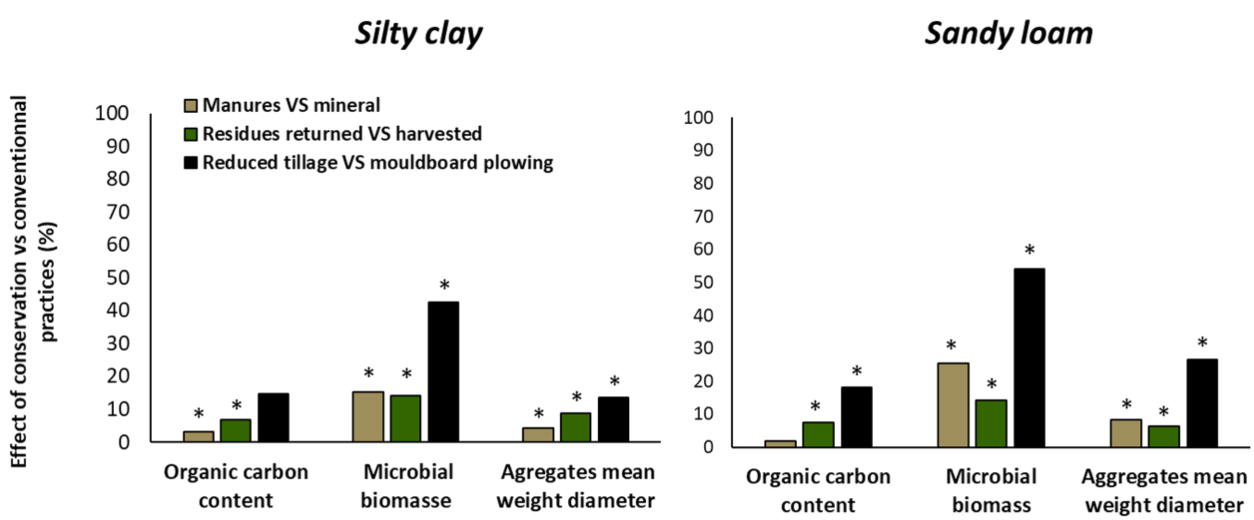

Figure 4. Graphical summary of the differences (%) between farm manures and the N-free mineral control (KP), returning the residues to the soil and harvesting them, as well as reduced tillage and ploughing for various surface soil health indicators (organic matter, microbial biomass, weighted mean diameter of water-stable aggregates).

The surface soil health indicators (organic carbon, microbial biomass and aggregate diameter) were, on average, 14% to 58% higher with reduced tillage than with ploughing (Samson et al., 2020a). In general, reduced tillage has a very positive impact on aggregation and on carbon accumulation in the soil surface (Sheehy et al., 2015). In fact, reduced tillage protects the aggregates from the physical action of ploughing on the aggregates themselves and on their stabilizing agents, such as fungal hyphae and roots (Figure 5). The increased stability of the surface soil aggregates is also promoted with reduced tillage through the accumulation of carbon compounds derived from the crop residues and microbial activity (Holland and Coleman, 1987). In fact, organic matter is known to be involved in stabilizing soil's aggregates and organic matter by increasing cohesion between the particles within the aggregate and increasing their hydrophobicity (Abiven et al., 2009). Fresh organic matter being included in stable aggregates then reduces its mineralization rate by limiting access to microorganisms.

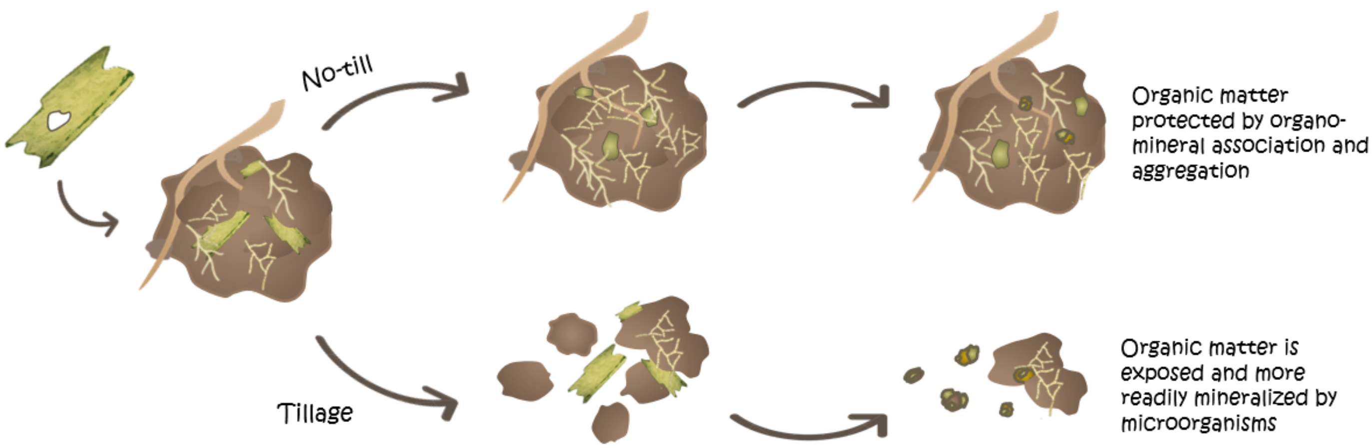

Figure 5. Impact of tilling on aggregate stability and on stabilization of fresh organic matter in the soil.

Our results showed that, even over a 10-year horizon, the influence of farming practices on soil health indicators can be substantial and can also vary depending on the combinations of practices and/or soil type. As previously suggested by some authors (Bissonnette et al. 2001; Viaud et al. 2011), our results showed a synergy between reduced tillage and returning residues and farm manures to the soil. The positive effect of the organic amendments on the soil health indicators was much higher when combined with reduced tillage than when combined with ploughing. One of the reasons for this outcome is that reduced tillage concentrates the organic amendments at the surface (within the 0-10 cm sampling area), while ploughing dilutes the organic inputs over a greater depth (Angers and Eriksen-Hamel 2008).

Is all soil organic matter the same?

Our results also highlighted the importance of the biochemical quality of the organic amendment for improving soil health and fertility (Samson et al., 2020b). Returning mature crop residues (high C/N and high lignin concentration) to the soil had a greater impact on total soil organic matter concentration of the topsoil (0-10 cm) than using farm manures (Figure 3). However, the crop residues mainly promoted organic carbon accumulation in a fraction of soil organic matter (LF) having a relatively low residence time in soil and had no impact on the soil nitrogen reserves (Figure 6). Conversely, farm manures (especially poultry manure and cattle manure) promoted carbon and nitrogen accumulation in more labile fractions of the soil organic matter (coarse-MAOM), thereby contributing to maintain and improve soil fertility over the long term (Nyiraneza et al. 2010; Webb et al. 2013) (Figure 6).

concentration and low C/N ratio (Cotrufo et al., 2013), such as farm manures. In fact, this type of organic amendment stimulates microbial activity and results in the formation of microbial by-products with a high propensity for organo-mineral associations (Kögel-Knabner et al., 2008), leading to long-term carbon stabilization in soil. However, stabilization of these organic products on soil mineral surfaces is possible only if reactive mineral surfaces are present in the soil and not already saturated with organic matter (Hassink, 1997). This is why, in our study, using poultry and dairy manure enabled stable organo-mineral complexes to form, but only in the silty clay soil, given its higher clay content (Figure 6).

Swine manure, however, did not have the same positive impact on soil health and fertility, possibly due to its lower carbon concentration and high concentration of NH4-N and soluble compounds (Morvan et al., 2006). These characteristics may have

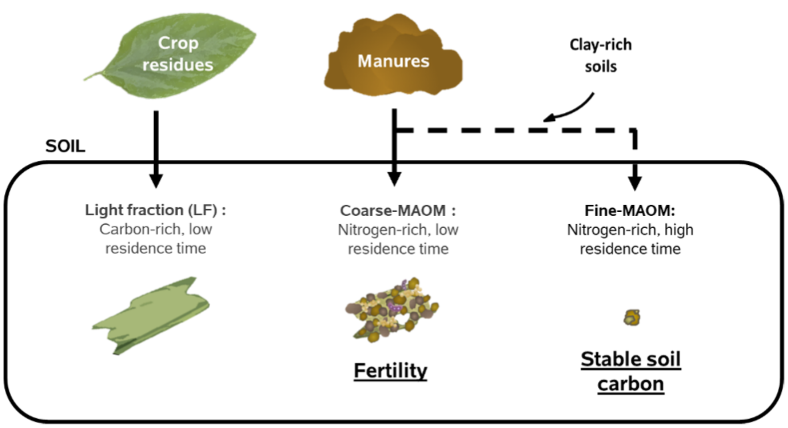

Figure 6. Graphical summary of the impact of the type of organic amendment on carbon and nitrogen accumulation within fractions of soil organic matter contributing to fertility or soil carbon storage.

Returning the crop residues to the soil had no impact on carbon and nitrogen accumulation in the fine and stable fractions of the soil organic matter (fine MAOM), and therefore did not significantly contribute to carbon stabilization over the long term. Poultry manure and cattle manure, however, did promote carbon and nitrogen accumulation in the stable fractions of the soil organic matter, but only in the silty clay.

This observation is consistent with the conceptual models of soil organic matter stabilization that attributes the formation of stable soil organic matter to inputs of organic amendments with a low lignin

stimulated mineralization of the soil's native organic matter, or even promoted leaching of a portion of the soluble organic compounds from the pig manure into the deeper layers (Angers et al., 2010). This is a reminder of the fact that, in addition to the overall positive impact of farm manures on soil health and fertility, some specific environmental issues can be associated with using them in an agricultural context. These issues remind us of the interconnectedness of all aspects of an agro-ecosystem, the complexity of their interactions, and the challenge of developing productive, sustainable and environmentally friendly cropping systems.

Do surface soil health and soil organic carbon stocks always go hand in hand?

Increasingly more private and government entities are becoming interested in the potential role of agricultural soils in combating climate change due to their considerable potential for sequestration of atmospheric carbon (Minasny et al. 2017) and other benefits resulting from that, such a potential improvement in soil health and a better resilience of the agri-food system to climate change (Lal et al., 2011). As such, a number of countries are currently developing policies to promote practices that enable carbon to be stored in agricultural soils. The Government of Canada itself recently announced that it will invest in a natural climate solutions fund for agriculture.

Currently, though, it is still very hard to accurately quantify the true impact of an agricultural practice on soil carbon stocks, especially due to the spatio-temporal variability of soil carbon concentration, the costs associated with the measures involved, and the lack of accuracy with the predictive models (Paustian et al., 2016). Also, the standardized procedures for measuring and tracking organic carbon stocks in soils currently suggest a sampling depth of 30 cm (FAO 2020). This recommendation is based on the premise that the soil's deep carbon is very stable and usually doesn't react much (or at all) to farming practices. However, recent studies have shown that, under certain conditions, farming practices, such as tillage and crop rotations, can considerably influence the organic carbon stocks below the first 30 centimetres of soil (Osanai et al. 2020).

Our own results showed that changes in subsurface carbon stocks could be significant to the point of dictating the soil's overall response to different agricultural practices (Samson et al., 2021). In fact, the impact of the different treatments on the carbon stocks was much lower in the first 15 cm of soil (0.36 to 0.76 kg C m-2) than in the underlying layers (up to 2.3 kg C m-2 for the 30-45 cm layer) (Figure 7). Thus, when the entire depth of the profile was considered (0-60 cm), it was the effect of agricultural practices on deep soil carbon that influenced the response of the whole soil's carbon stocks to the various cropping systems.

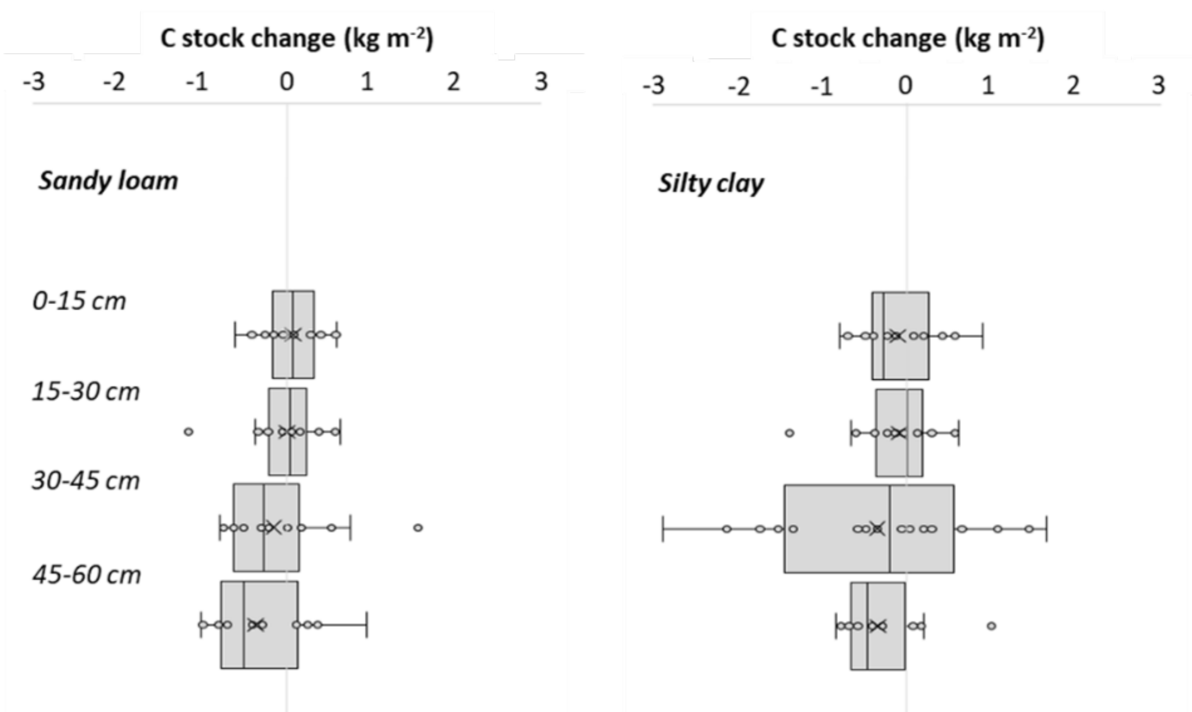

Figure 7. Distribution of the changes seen in soil carbon stocks at different depths after 8 years of treatments.

In addition, the treatments' impact on the carbon stocks varied based on the depth. In the sandy loam, for example, the soil conservation practices (reduced tillage, residue return, and use organic fertilizers) usually (but not always) resulted in higher carbon stocks than the conventional treatments in the 0-15 cm layer. However, in the 15-30, 30-45 and 45-60 cm layers, the treatments' impact was quite different and highly dependent on the interactions among the various practices. As such, for ploughing, the carbon stocks below the surface layer (>15 cm) were higher when the use of liquid farm manures (especially swine manure) was combined with returning the residues to the soil, than when combined with harvesting the residues (Figure 8). The high content of soluble organic matter in the liquid manures (especially swine manure) (Morvan et al., 2006) probably promoted leaching and accumulation of the organic matter from those fertilizers into the soil's deeper layers (Angers et al., 2010). That accumulation of C and N at depth was particularly evident when the presence of crop residues under the ploughing layer enabled it to be retained. Under the cool, wet conditions prevailing at the experimental site, deep microbial activity is slowed, compared with the surface, which enables the deeper organic matter to be conserved over the long term. When ploughing was combined with using mineral fertilizers, however, the deep carbon stocks were higher when the residues were harvested than when they were returned to the soil (Figure 8). Under similar conditions, Shahbaz et al. (2017) also found that decadal mineral nitrogen fertilisation considerably reduced subsoil (25-60 cm) carbon stocks in a tilled Luvisol. Thus, deep carbon stocks seem to be especially sensitive to the different combinations of fertilizer sources and residue management practices when the soil is ploughed and the organic matter and nutrients/nutrients are buried at depth.

Under the circumstances of our study, the changes in carbon stocks below the surface (>15 cm) were so great compared with those of the surface layer that they determined the response of the entire soil profile to the management practices. These results show that deep carbon dynamics need to be specifically factored in and that the recommendations for managing carbon stocks in agricultural soils should extend beyond the recommendation for the first 30 centimetres of soil, at least in the pedoclimatic conditions of Eastern Canada

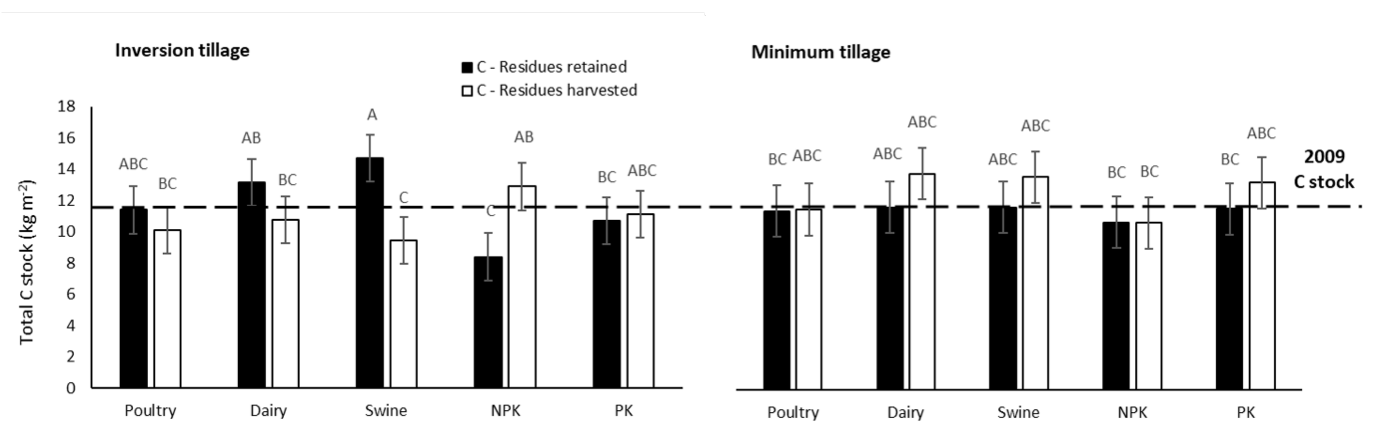

Figure 8. Total soil carbon stocks (0-60 cm) after 8 years of treatments in sandy loam. Different letters indicate a significant difference among the treatments.

The results of this project clearly demonstrate the complexity of the agricultural, climate, biogeochemical, and physical factors that can affect the different services provided by agricultural soils under field crop production systems. In addition to this inherent complexity, there are also the financial, social and environmental issues associated with managing farm businesses. In fact, in order to survive over the long term, agricultural productions must obviously be profitable and therefore obtain acceptable yields. Producers must also consider the sustainability of their business. This inevitably means maintaining (or improving) the health of their soils. Agricultural producers must also address the growing concerns of the public and government institutions pertaining to agriculture's impact on the environment and human health. So, both locally and internationally, we're feeling a movement towards the development of an agro-ecological approach for handling the economic, social and environmental issues associated with producing food. Although it's easy to imagine that, by adopting a so-called "conservation" farming practice, a producer will necessarily optimize both the agronomic and environmental services provided by agricultural soils, the reality is a little more complex.

In fact, practices that help improve crop yields and/or soil health directly impact the profitability and sustainability of the farm business. This can facilitate the acceptability of these practices and their adoption by more producers. In contrast, agricultural producers will be reluctant to voluntarily adopt practices for storing atmospheric carbon in the soil, unless those practices also have a positive impact on soil health or their crop yields. In fact, agricultural producers answer to the rules of a liberalized market and must therefore offer a globally competitive product. By accepting an increase in costs or a decrease in yield in the name of sustainability of the Canadian agri-food system and/or the fight against climate change, an agricultural producer is therefore potentially in a precarious position vis-à-vis the rest of the market. In this context, it may therefore be relevant to develop financial incentives for carbon sequestration in agricultural soils and/or maintenance or improvement of soil health indicators. However, the incentives should be based on reliable measurements and/or predictions tailored to farms' pedoclimatic and cropping context.

Yet, this solution would still present significant challenges (Smith et al. 2020). Current strategies to report and verify soil carbon changes at the farm level include direct measurements and process-based modelling, both of which involve certain limitations (Smith et al., 2019). In fact, the measurement of on-farm carbon stock changes would be very costly, particularly due to the spatial and temporal variability, which requires a large number of samples in order to obtain a representative assessment of the changes in stocks under different farming practices (de Gruijter et al., 2018). It has also been shown that the magnitude of the annual carbon stock change caused by annual weather conditions can sometimes exceed the stock changes associated with management practices, at least over a decadal time scale (Dimassi et al. 2014; Paustian et al. 2016). When considering the high sampling costs associated with intensive measurement to account for soil spatial and temporal variability, process-based models may be favored. However, this strategy also comes with great challenges, partly due to the sheer magnitude of factors to be considered and parameterized in the model to obtain reliable predictions at the farm's scale level (Otway et al. 2020).

Efforts will therefore have to be invested in the development of new sensor technologies that could make it possible to do quick, low-cost sampling and measurements. These efforts may also benefit from the improvement of process-based models, who require high-quality data generated from consistent measurement protocols under various soil types, climate zones, land-use types and soil management practices over long periods of time. This also highlights the need for the Canadian government to support long-term diachronic scientific trials in agriculture. Standardized sampling and measurement protocols on these trials could help build a much needed and very valuable national database that could be used to develop a reliable national and greenhouse gas mitigation programme in agriculture (Paustian, et al., 2016).

Furthermore, although not examined in this study, it is also important to factor in other major but sometimes under-estimated processes that enter into the equation. For example, when looking at the role of agricultural soils in the fight against climate change, CO2 sequestration is often put forward, but it's important not ignore the other greenhouse gases that can be produced by agricultural soils. Thus, if a farm practice enables carbon to be stored in the soil, but results in a similar or greater release of CO2 equivalents in the form of N2O, its impact on climate change will not necessarily be as expected (Li et al. 2005; Zaehle et al. 2011).

Incentives for carbon sequestration in agricultural soils could only be based on rough estimates, or on broad best management practices recommendations with a low risk level relative to other agro-environmental services provided by soils, but imply a large uncertainty based on actual carbon sequestration rates.

Conclusion

Agriculture and food are key components of the Canadian economy. The overarching challenges that the planet has been facing for a number of decades remind us of the importance of maintaining our ability to produce food and to develop effective adaptation and mitigation strategies for dealing with climate change. Although carbon sequestration in agricultural soils has been identified as one of the most attractive solutions in the fight against climate change, the results of our study show that there could sometimes be a trade-off among crop yields, surface soil health, and carbon sequestration within the entire soil profile.

In fact, under the conditions of our study, although reduced tillage was generally beneficial for surface soil health, its impact on yield varied depending on soil type and crop. As for returning residues to the soil, it sometimes negatively impacted yield, but some positive impacts on surface soil health and deep carbon storage were seen. Overall, the impact of farm manures was influenced by their biochemical quality. As such, swine manure sometimes led to better yields than cattle and poultry manure, but its positive impact on surface soil health was less significant. In contrast, poultry manure and cattle manure promoted preferential accumulation of carbon and nitrogen in the labile and stable fractions of soil organic matter, thereby helping improve both soil fertility and soil carbon storage over the long term. However, over the time period studied, these farm manures didn't always lead to yields as high as with the mineral fertilizer, especially for corn, given its high nitrogen requirements. To successfully develop a broadly applicable agro-ecological approach, other innovative practices will have to be incorporated, such as integrating cover crops and green fertilizers. Predictive models will also have to keep being developed, factoring in a wide range of practices combinations and pedoclimatic conditions.

However, these results should not be viewed as a barrier to adopting soil conservation practices, but as a call to recognize the inherent complexity of agro-ecosystems and to invest in science and the development of reliable tools for measuring and predicting. They are also a call to recognize the true value of all the ecosystem services provided by agricultural soils. Although crop yields and the profitability of the farm business are currently the main factors driving the market and decision-making, countries that manage to invest in the sustainability of their agri-food systems will necessarily benefit over the long term. If it is able to recognize that value, Canada will invest in the resilience of its agri-food system and will be able to rely on a return on its investment in the years to come. Nothing is more important than that because, in the words of Dr. Swaminathan, agronomist and first recipient of the Nobel Food Prize: "If agriculture goes wrong, nothing else will have a chance to go right."

References

Abiven, S., Menasseri, S., Chenu, C., 2009. The effects of organic inputs over time on soil aggregate stability – A literature analysis. Soil Biology and Biochemistry 41, 1-12.

Angers, D., Eriksen-Hamel, N., 2008. Full-inversion tillage and organic carbon distribution in soil profiles: A meta-analysis. Soil Science Society of America Journal 72, 1370-1374.

Angers, D., Chantigny, M., Macdonald, J., Rochette, P., Côté, D., 2010. Differential retention of carbon, nitrogen and phosphorus in grassland soil profiles with long-term manure application. Nutrient Cycling in Agroecosystems 86, 225-229.

Bissonnette, N., Angers, D.A., Simard, R.R., Lafond, J., 2001. Interactive effects of management practices on water-stable aggregation and organic matter of a Humic Gleysol. Canadian Journal of Soil Science 81, 545-551.

Bloom, T., Sylvester-Bradley, R., Vaidyanathan, L., Murray, A., 1988. Apparent recovery of fertilizer nitrogen by winter wheat. Nitrogen efficiency in agricultural soils, 27-37.

Brainard, D.C., Haramoto, E., Williams, M.M., Mirsky, S., 2013. Towards a no-till no-spray future? Introduction to a symposium on nonchemical weed management for reduced-tillage cropping systems. Weed Technology 27, 190–192.

Cambardella, C.A., Moorman, T.B., Singer, J.W., 2010. Soil nitrogen response to coupling cover crops with manure injection. Nutrient cycling in agroecosystems 87, 383-393.

Charles, A., Vanasse, A., Van Eerd, L.L., Tremblay, N., Bourgeois, G., Lynch, D.H., 2017. Meta-analysis of cover cropping systems: The effects of cover crops on subsequent cash crop yields and nitrogen contribution. ASA, CSSA and SSSA International Annual Meetings. Tampa, FL.

Cotrufo, M.F., Wallenstein, M.D., Boot, C.M., Denef, K., Paul, E., 2013. The Microbial Efficiency Matrix Stabilization (MEMS) framework integrates plant litter decomposition with soil organic matter stabilization: do labile plant inputs form stable soil organic matter? Global Change Biology 19, 988-995.

Day, J., Hallahan, C., Sandretto, C., Lindamood, W., 1999. Pesticide use in US corn production: Does conservation tillage make a difference? Journal of soil and water conservation 54, 477–484.

Dimassi, B., Mary, B., Wylleman, R., Labreuche, J., Couture, D., Piraux, F., Cohan, J.-P., 2014. Long-term effect of contrasted tillage and crop management on soil carbon dynamics during 41 years. Agriculture, Ecosystems and Environment 188, 134-146.

FAO. 2020. A protocol for measurement, monitoring, reporting and verification of soil organic carbon in agricultural landscapes – GSOC-MRV Protocol. Rome. https://doi.org/10.4060/cb0509en

Ganeshamurthy, A.N., Sammi Reddy, K., 2000. Effect of Integrated Use of Farmyard Manure and Sulphur in a Soybean and Wheat Cropping System on Nodulation, Dry Matter Production and Chlorophyll Content of Soybean on Swell-Shrink Soils in Central India. Journal of Agronomy and Crop Science 185, 91-97.

Grandy, A.S., Neff, J.C., 2008. Molecular C dynamics downstream: the biochemical decomposition sequence and its impact on soil organic matter structure and function. Science of the Total Environment 404, 297-307.

de Gruijter, J.J., McBratney, A.B., Minasny, B., Wheeler, I., Malone, B.P., Stockmann, U., 2018. Farm-scale soil carbon auditing. Pedometrics. Springer, pp. 693-720.

Hassink, J., 1997. The capacity of soils to preserve organic C and N by their association with clay and silt particles. Plant and Soil 191, 77–87.

Hobbs, P.R., Sayre, K., Gupta, R., 2008. The role of conservation agriculture in sustainable agriculture. Philosophical Transactions of the Royal Society B: Biological Sciences 363, 543-555.

Holland E, Coleman DC, 1987. Litter placement effects on microbial and organic matter dynamics in an agroecosystem. Ecology 68, 425-433.

Kögel-Knabner, I., Guggenberger, G., Kleber, M., Kandeler, E., Kalbitz, K., Scheu, S., Eusterhues, K., Leinweber, P., 2008. Organo-mineral associations in temperate soils: Integrating biology, mineralogy, and organic matter chemistry. Journal of Plant Nutrition and Soil Science 171, 61-82.

Lal, R., Delgado, J., Groffman, P., Millar, N., Dell, C., Rotz, A., 2011. Management to mitigate and adapt to climate change. Journal of Soil and Water Conservation 66, 276-285.

Lankoski, J., Ollikainen, M., Uusitalo, P., 2006. No-till technology: benefits to farmers and the environment? Theoretical analysis and application to Finnish agriculture. European Review of Agricultural Economics 33, 193-221.

Li, C., Frolking, S., Butterbach-Bahl, K., 2005. Carbon sequestration in arable soils is likely to increase nitrous oxide emissions, offsetting reductions in climate radiative forcing. Climatic Change 72, 321-338.

Masilionyte, L., Maiksteniene, S., Kriauciuniene, Z., Jablonskyte-Rasce, D., Zou, L., Sarauskis, E., 2017. Effect of cover crops in smothering weeds and volunteer plants in alternative farming systems. Crop Protection 91, 74-81

Minasny, B., Malone, B.P., McBratney, A.B., Angers, D.A., Arrouays, D., Chambers, A., Chaplot, V., Chen, Z.-S., Cheng, K., Das, B.S., 2017. Soil carbon 4 per mille. Geoderma 292, 59-86.

Mirsky, S.B., Ryan, M.R., Curran, W.S., Teasdale, J.R., Maul, J., Spargo, J.T., Moyer, J., Grantham, A.M., Weber, D., Way, T.R., 2012. Conservation tillage issues: Cover crop-based organic rotational no-till grain production in the mid-Atlantic region, USA. Renewable Agriculture and Food Systems 27, 31-40.

Morvan, T., Nicolardot, B., Péan, L., 2006. Biochemical composition and kinetics of C and N mineralization of animal wastes: a typological approach. Biology and Fertility of Soils 42, 513–522.

Nyiraneza, J., Chantigny, M., N'Dayegamiye, A., Laverdiere, M., 2010. Long-Term Manure Application and Forages Reduce Nitrogen Fertilizer Requirements of Silage Corn-Cereal Cropping Systems. Agronomy Journal 102, 1244–1251.

Ogle, S.M., Swan, A., Paustian, K., 2012. No-till management impacts on crop productivity, carbon input and soil carbon sequestration. Agriculture, Ecosystems and Environment 149, 37-49.

Oldfield, E.E., Bradford, M.A., Wood, S.A., 2019. Global meta-analysis of the relationship between soil organic matter and crop yields. Soil, pp. 15-32.

Otway, J., 2020. Farm-Scale Modelling for the Spatio-Temporal Prediction of Soil Carbon Sequestration in South-Western Australia: Bringing Soil Carbon Modelling to the Farm Gate

Parkin, T., Kaspar, T., Singer, J., 2006. Cover crop effects on the fate of N following soil application of swine manure. Plant and Soil 289, 141–152.

Paustian, K., Lehmann, J., Ogle, S., Reay, D., Robertson, G.P., Smith, P., 2016. Climate-smart soils. Nature 532, 49-57.

Pittelkow, C.M., Linquist, B.A., Lundy, M.E., Liang, X., van Groenigen, K., Lee, J., van Gestel, N., Six, J., Venterea, R., van Kessel, C., 2015. When does no-till yield more? A global meta-analysis. Field Crops Research 183, 156-168.

Samson, M.-E., Menasseri-Aubry, S., Chantigny, M., Angers, D., Royer, I., Vanasse, A., 2019. Crop response to soil management practices is driven by interactions among practices, crop species and soil type. Field Crops Research 243, 107623.

Samson, M.-É., Chantigny, M.H., Vanasse, A., Menasseri-Aubry, S., Royer, I., Angers, D.A., 2020a. Management practices differently affect particulate and mineral-associated organic matter and their precursors in arable soils. Soil Biology and Biochemistry, 107867.

Samson, M.-É., Chantigny, M.H., Vanasse, A., Menasseri-Aubry, S., Angers, D.A., 2020b. Coarse mineral-associated organic matter is a pivotal fraction for SOM formation and is sensitive to the quality of organic inputs. Soil Biology and Biochemistry, 107935.

Samson, M.-É., Chantigny, M.H., Vanasse, A., Menasseri-Aubry, S., Royer, I., Angers, D.A., 2021. Subsurface C and N stock changes drive whole-soil profile response to agricultural management practices. Article accepted with major revision, Agriculture, ecosystems and environment.

Schipanski, M., Drinkwater, L., Russelle, M., 2010. Understanding the variability in soybean nitrogen fixation across agroecosystems. Plant Soil 329, 379–397.

Shahbaz, M., Kuzyakov, Y., Maqsood, S., Wendland, M., Heitkamp, F., 2017. Decadal nitrogen fertilization decreases mineral-associated and subsoil carbon: a 32-year study. Land degradation & development 28, 1463-1472.

Sheehy, J., Regina, K., Alakukku, L., Six, J., 2015. Impact of no-till and reduced tillage on aggregation and aggregate-associated carbon in Northern European agroecosystems. Soil & Tillage Research 150, 107-113.

Smith, P., Soussana, J.F., Angers, D., Schipper, L., Chenu, C., Rasse, D.P., Batjes, N.H., van Egmond, F., McNeill, S., Kuhnert, M., 2020. How to measure, report and verify soil carbon change to realize the potential of soil carbon sequestration for atmospheric greenhouse gas removal. Global Change Biology 26, 219-241.

Soane, B.D., Ball, B.C., Arvidsson, J., Basch, G., Moreno, F., Roger-Estrade, J., 2012. No-till in northern, western and south-western Europe: A review of problems and opportunities for crop production and the environment. Soil and Tillage Research 118, 66-87.

Toliver, D., Larson, J., Roberts, R., English, B., Ugarte, D., West, T., 2012. Effects of No-Till on Yields as Influenced by Crop and Environmental Factors. Agronomy Journal 104, 530-541.

Tremblay, N., Bouroubi, Y., Belec, C., Mullen, R.W., Kitchen, N., Thomason, W., Ebelhar, S., Mengel, D., Raun, W., Francis, D.D., Vories, E., Ortiz-Monasterio, I., 2012. Corn Response to Nitrogen is Influenced by Soil Texture and Weather. Agronomy Journal. 104, 1658-1671.

UNCCD (United Nations Conventions to Combat Desertification), 2017. Global Land Outlook. Bonn, Germany.

Viaud, V., Angers, D., Parnaudeau, V., Morvan, T., Menasseri-Aubry, S., 2011. Response of organic matter to reduce tillage and animal manure in a temperate loamy soil. Soil Use And Management 27, 84-93.

Webb, J., Seeney, F., Sylvester-Bradley, R., 1998. The response to fertilizer nitrogen of cereals grown on sandy soils. J. Agric. Sci. 130, 271–286.

Webb, J., Sorensen, P., Velthof, G., Amon, B., Pinto, M., Rodhe, L., Salomon, E., Hutchings, N., Burczyk, P., Reid, J., 2013. An assessment of the variation of manure nitrogen efficiency throughout Europe and an appraisal of means to increase Manure-N efficiency. Advances in Agronomy 119, 371–442.

Zaehle, S., Ciais, P., Friend, A.D., Prieur, V., 2011. Carbon benefits of anthropogenic reactive nitrogen offset by nitrous oxide emissions. Nature Geoscience 4, 601-605.