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The impact of land conversion from boreal forest to agriculture on soil health indicators

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Abstract

Climate change is creating opportunities for agricultural expansion northward into the boreal forest. Converting forested land to agricultural land generally results in significant losses of organic matter (OM), which can impact soil health (SH). The objectives of this study were to assess the effects of land conversion on indicators of SH and to use the Comprehensive Assessment for Soil Health (CASH) framework to integrate measures of these indicators into a score to evaluate land conversion effects. Total carbon and nitrogen were also measured in this study. Soils (0–5 and 5–15 cm) were collected from six dairy farms near Thunder Bay, ON, that included a mature forest, a field converted from forest to agriculture <10 years ago and a field converted from forest to agriculture >50 years ago. Land conversion resulted in significant declines in permanganate oxidizable carbon, wet aggregate stability, soil respiration, and concentrations of OM, autoclave citrate extractable protein, total nitrogen, and total carbon. Lower CASH scores in the soils converted to agriculture are interpreted to represent a decline in SH but the scores, along with soil organic matter (SOM) concentrations, remain high (CASH = 80; OM = 6%). There was no effect of time since conversion, suggesting that any degradation to SH happens quickly and is closely tied to declines in SOM.

Key words: dairy farms, CASH framework, land conversion, soil assessment, soil organic matter, soil respiration, permanganate oxidizable carbon, wet aggregate stability

Résumé

Le réchauffement climatique multiplie les possibilités d'expansion de l'agriculture vers le nord, dans la forêt boréale. Convertir des boisés en terres agricoles engendre habituellement une forte perte de la matière organique, ce qui pourrait détériorer le sol. Les auteurs voulaient évaluer les conséquences d'une telle conversion sur les indicateurs de la vitalité du sol et recourir au cadre CASH (« Comprehensive Assessment for Soil Health ») pour intégrer les valeurs de ces indicateurs et obtenir une note évaluant les conséquences de la transformation du sol. L'étude a aussi permis d'établir la quantité totale de carbone et d'azote. Des échantillons de sol (0–5 cm et 5–15 cm) ont été prélevés dans six exploitations laitières près de Thunder Bay (Ontario), où se trouvaient une forêt mature, un champ issu de la conversion d'une forêt en terre arable il y a moins de dix ans et un autre venant d'une telle conversion réalisée il y a plus de cinquante ans. La conversion des terres entraîne une baisse importante de la quantité de carbone oxydable au permanganate, de la stabilité des agrégats humides, de la respiration du sol, de la concentration de matière organique, de protéine d'extractible au citrate en autoclave, d'azote total et de carbone total. La note CASH plus faible des sols transformés en terres arables révèle une diminution de la vitalité du sol. Cependant, cette note demeure élevée, à l'instar de la teneur en matière organique (CASH = 80; MO = 6 %). Le temps écoulé depuis la conversion n'a aucune conséquence, signe que le sol se détériore rapidement quand il le fait, et que cette détérioration est étroitement liée à une diminution de la quantité de matière organique dans le sol. [Traduit par la Rédaction]

Mots-clés : exploitation laitière, cadre CASH, conversion des terres, évaluation du sol, matière organique du sol, respiration du sol, carbone oxydable au permanganate, stabilité des agrégats humides

Introduction

Changes in climate are creating opportunities for agricultural expansion northward into the boreal forest, which will require the conversion of scrub brush and forest to agricultural land (King et al. 2018; Bahadur et al. 2021; Unc et al. 2021). Land clearing removes the forest canopy, increasing soil temperatures and altering soil moisture, which favors the decomposition of soil organic matter (SOM) and the release of carbon and nutrients (Houghton 1995; Wei et al. 2014). The significant losses of SOM documented after land conversion are often rapid because decomposition is occurring at a faster rate than organic matter (OM), is being returned to the soil and practices, such as tillage, destroy, and disrupt the formation of aggregates. In Eastern Canada, land clearing to support agriculture has resulted in a 22% decrease in soil carbon compared with uncleared adjacent areas (Angers et al. 1995) and in boreal regions, soil organic carbon stocks have decreased approximately 31% where conversion has occurred (Wei et al. 2014).

In addition to being a storehouse of carbon and nutrients, SOM contributes to the maintenance of soil structure, water holding capacity, and a diverse microbial community (Wall et al. 2012; Cano et al. 2018). Significant losses of SOM are synonymous with soil degradation (e.g., Matson et al. 1997) and the deterioration of the soil's ability to naturally support the needs of humans, plants, and animals (e.g., Karlen et al. 1997). Soil health (SH) has been defined by many but is inherently a metaphor that cannot be fully measured directly (Janzen et al. 2021). However, SH assessments are useful tools to examine how land management practices are impacting soil functions in time and space beyond the typical chemical properties used to describe soil fertility (Karlen et al. 1997).

Soil health assessments, such as the Comprehensive Assessment of Soil Health (CASH), integrate measurements of physical, chemical, and biological properties of soil that are indicators of soil functions. The CASH produces an overall score for a soil, along with scores for the individual indicators that have been used to evaluate the effects of land management practices on soil functioning. Assessing SH over time is viewed as being an indicator of sustainable management (Karlen et al. 1997) and the goal of the CASH score is to identify constraints to production at the site level to help increase land productivity while minimizing environmental impacts (Idowu et al. 2009). The CASH was developed using soils and agroecosystems in the northeastern USA but has been used outside of the area, often with an assessment of the sensitivity of the measured indicators to the management practices of interest (e.g., Congreves et al. 2015).

In this study, we evaluated the effect of land conversion on soil physical, chemical, and biological indicators using the CASH framework in two agricultural areas near Thunder Bay, Ontario. Soils were collected from forests, recently converted fields (<10-year agriculture) and established agricultural fields (>50-year agriculture) in the Murillo and Slate River areas. We hypothesize that the forests will have the highest SH scores and that land clearing and conversion will result in a decline in SH scores and detrimental changes in SH indicators; that changes will be greatest in the >50-year agriculture sites; and that changes will be most pronounced near the soil surface.

Materials and methods

Study area and soil sampling

Six farms in the Thunder Bay area (45°31′N–48°17′N, 89°30′W–89°22′W; Fig. 1) were sampled between July and August 2019 with three farms in the Murillo area and three farms in the Slate River area. Farmer participation was initiated through discussions at a rotational grazing workshop and extension work at the Lakehead University Agricultural Research Station. All farms are dairy operations and tile drained. Farmers use a combination of manure and mineral fertilizer at recommended rates to meet crop requirements and conservation tillage. The common N fertilizer included a blend of urea, ammonium sulfate, monoammonium phosphate, muriate of potash, and zinc sulfate. The crop rotation for the region is alfalfa (*Medicago sativa*), silage corn (*Zea mays*), barley (*Hordeum vulgare*), or winter wheat (*Triticum aestivum*) (Supplementary Table S5). Each farm operation included a mature mixed-wood forest, fields that had been cultivated less than 10 years ago (<10-year agriculture), and fields that had been cultivated more than 50 years ago (>50-year agriculture).

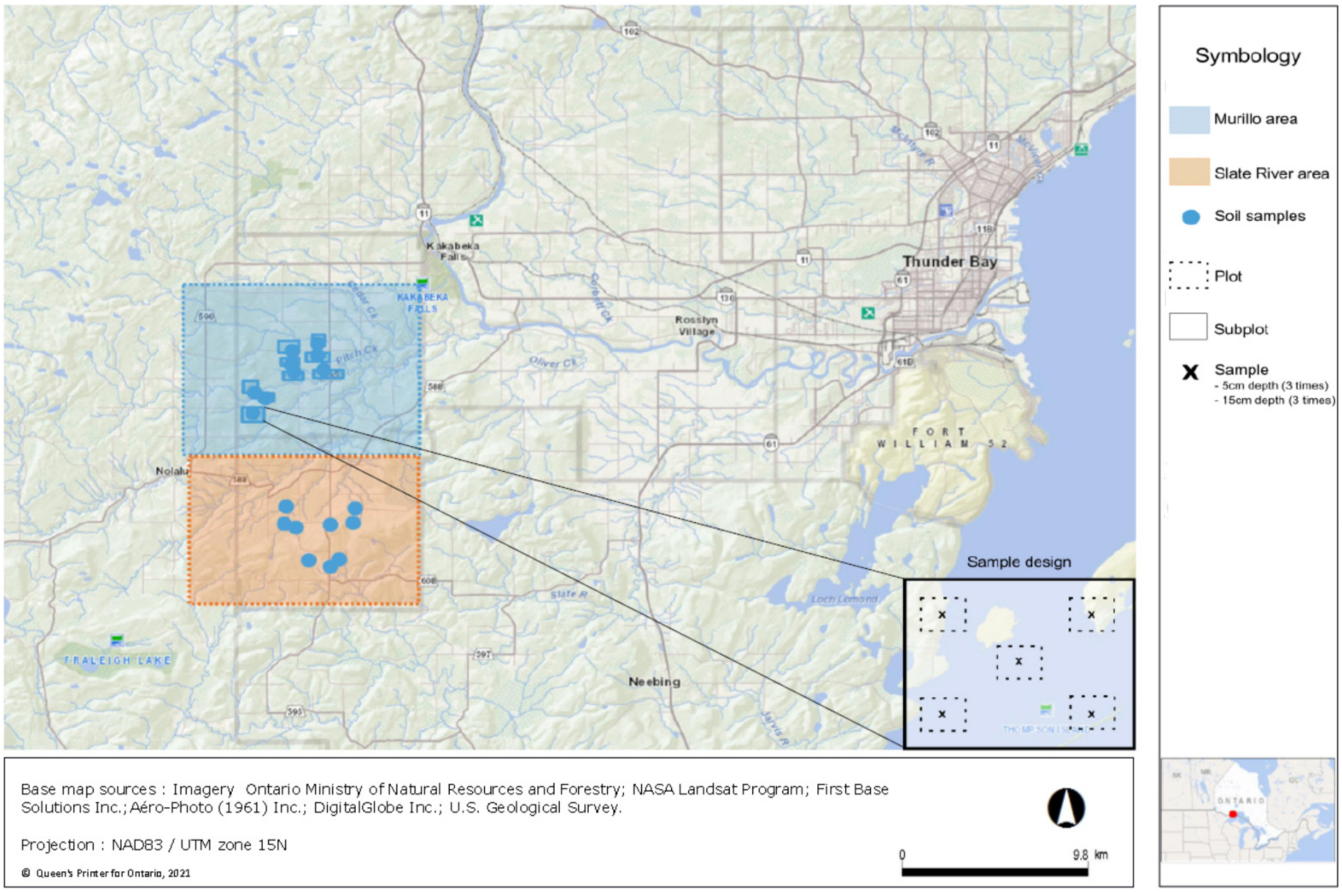
The Murillo area is part of an end moraine, consisting of large deposits of till and boulders, with minor inclusions of water-laid alluvial silt, sand, and gravel deposited by glacial streams. End moraine layers include unsorted and unstratified materials of varying sizes and can both underlie and overlie sequences of layered silt, sand, and gravel. Also, end moraine water tables are generally low and have variable permeability and internal drainage, plus low compressibility and high bearing strength (Mollard and Mollard 1983). The Slate River area is part of a glaciolacustrine plain consisting of varved and massive, fine-grained material deposited in glacial lakes. Amounts of clay, silt, and sand vary depending on basin and depth. Usually, glaciolacustrine deposits consist of clay and silt with high water retention capacity, low permeability, and poor internal drainage. The Slate River area soils generally have low bearing strength and moderate to high compressibility (Mollard and Mollard 1983).

Soils were collected using a soil split-core sampler (AMS Soil Samplers, Inc., American Falls, Idaho) at five locations in each cropped field and forest (at each corner and in the center). At each location, a total of three subsamples were collected to 15 cm in the mineral soil, divided by depth (0–5 and 5–15 cm) (Malone et al. 2009; Oertel et al. 2016) and composited. Forest soil samples were taken after removing the O horizon, which was largely plant litter. All samples were transported in a cooler to the laboratory at Lakehead University where they were air-dried and passed through an 8- and 2-mm sieve, as recommended by the CASH framework (Moebius-Clune et al. 2017). From each composite sample, a 1 L volume of soil was shipped to the Cornell Soil Health Laboratory in Ithaca, NY, and the USDA Forest Service Northern Research Station in Grand Rapids, MN, for analysis.

Physical SH indicators

The physical soil indicators measured in this study were texture, wet aggregate stability (WAS), and surface and subsurface penetration resistance. Texture was assessed at Cornell using the Kettler method (Kettler et al. 2001) to determine particle size distribution by sieving and sedimentation. Wet aggregate stability was assessed at Cornell using a rainfall simulator to measure the soil aggregate's resistance to disaggregation with moisture and raindrop impact. A force of 0.5 J was applied for 5 minutes to soil in a sieve that contained

Fig. 1. Murillo and Slate River areas and sample design located in the Thunder Bay area in Northern Ontario, Canada. [Colour online]



a known weight of soil aggregates ranging in size from 0.25 to 2.00 mm. The Cornell rainfall simulator delivers 12.5 mm of water in 5 minutes (Moebius et al. 2007). Using the Sjoerd (2002) procedure, penetration resistance was measured in the field over the 0–15 cm depth (surface) and 15–30 cm (subsurface) depth using a Dickey–John penetrometer.

Chemical SH indicators

The chemical soil properties measured in this study were pH, phosphorus (P), potassium (K), magnesium (Mg), iron (Fe), manganese (Mn), zinc (Zn), total C (TC), and total N (TN). All the measurements were completed at the USDA Forest Service Northern Research Station in Grand Rapids, MN. Soil pH was measured in a suspension of two parts water to one part soil determined by a Lignin pH robot (LIGNIN LLC) (Moebius-Clune et al. 2017). Phosphorus, K, Mg, Fe, Mn, and Zn were extracted using a modified Morgan's solution, an ammonium acetate plus acetic acid solution, buffered at pH 4.8. The extracted slurry was filtered through filter paper and analyzed with an inductively coupled plasma emission spectrometer (ICP Arcos, Spectro Analytical Instruments, Kleve, Germany; Moebius-Clune et al. 2017). Total N and TC were analyzed using 0.5 g of soil combusted in a LECO CHN 628 Series total elemental analyzer (LECO Corporation, St. Joseph, Michigan), using the CHN1 (stock) method, at a temperature of 950 °C in the furnace, and 850 °C after burned.

Biological SH indicators

The biological soil properties in this study included OM, autoclave citrate extractable (ACE) protein, soil respiration (Resp), and permanganate oxidizable carbon (POXC) and were measured at Cornell. OM was determined by using loss on ignition (Broadbent 1965). A total of 10 g of soil was weighed and heated to 500 °C in a furnace. The exposure to higher temperature removed the carbonaceous material while retaining mineral materials in the sample. The resulting difference loss is the OM. The Autoclave Citrate Extractable Protein Index, adapted from Wright and Upadhyaya (1996), was equivalent to ACE protein in the OM (Moebius-Clune et al. 2017). A total of 3 g of soil was weighed and placed in a test tube with 24 mL of extractable sodium (0.02 mol/L, pH 7), then stirred for 5 minutes at 180 rpm and placed in the autoclave at 121 °C and 14.50 psi above atmospheric pressure for 30 minutes. Next, 2 mL of extract was clarified by centrifuging at 10 000 rpm to remove soil particles. A small subsample of this clarified solution was used in a standard colorimetric protein quantification assay (Bicinchonic Acid Assay), and the results were compared with a serum albumin standard curve of soil protein, using a BioTek (Winooski, Vermont) spectrophotometric plate reader (Moebius-Clune et al. 2017).

Soil respiration is a measure of microbial community activity and an indicator of diverse soil functions, such as nutrient transformation, mineralization, and solubilization (Krishnan et al. 2020). Microbial activity also contributes to stabilizing soil aggregates, facilitating soil aeration, infiltration, and carbon sequestration (Moebius-Clune et al. 2017). The heterotrophic Resp method is adapted from Zibilske (1994) and indicates the microbial metabolic activity of the soil (Allen et al. 2011). The laboratory methodology quantifies the CO_2 released from a rewetted air-dried soil after 4 days. Twenty gram of air-dried soil was weighed in an aluminum boat with perforations, and the boat was placed over two small filter papers in a glass jar. A pipette trap filled with 9 mL of 0.5 mol/L KOH was placed into the jar to trap the CO_2 during the 4 days of incubation. Using a pipette, distilled water (7.5 mL) was added to the jar to rewet the soil sample, so that capillary action could raise water into the soil. The jars were then sealed for 4 days at room temperature of 23.5 °C. The CO_2 respiration measurements were determined by observing the electrical conductivity in the KOH trap with a WTW ProfiLineCond 3310 electrical conductivity meter. Greater CO_2 indicates a more active microbial community in the soil (Moebius-Clune et al. 2017). Permanganate oxidizable carbon is a small part of the OM pool that is readily available as a food source for soil microbes (Moebius-Clune et al. 2017); it is also known as the labile fraction of soil C (Weil et al. 2003) and is a function of the rate at which the soil reacts with dilute potassium permanganate ($KMnO_4$; Weil et al. 2003). A hand-held colourimeter was used to determine the absorbance of the soil potassium permanganate solution at 550 nm. The colourimetry reading has an inverse linear relationship with POXC.

Overall SH score

The measured biological, chemical, and physical soil properties were integrated using the CASH framework to calculate a SH score for each category of conversion on each farm (Andrews et al. 2004). The SH score is calculated on a scale of 0–100 and scores are interpreted as very low (<40), low (40–55), medium (55–70), high (70–85), and very high (>85) (Moebius-Clune et al. 2017). Soil health scores were calculated for both soil depths, acknowledging that the framework was designed to represent SH in the top 0–15 cm of soil.

Statistical analysis

A Type III marginal linear mixed effects model was used to determine if the SH indicators and scores were affected by land conversion, soil depth and if there was an interaction effect. Fixed effects included time since conversion and soil depth. In the case of surface and subsurface resistance, the fixed effect was time since conversion. Time since conversion nested in farm was included a random effect for all indicators. Posthoc examinations of significant conversion effects were conducted using orthogonal contrasts to determine if 1. the forest soils differed from the agricultural soils and 2. if there was an effect of time since conversion on the measured indicators and scores. Pearson correlation coefficients for the physical, biological, and chemical indicators were represented using the full data set.

All analyses were conducted using SPSS 25 (IBM Corp 2019). Data are represented as means with standard errors.

Results

The concentration of Mg (589 ± 323 mg/kg), and proportions of silt and clay in the soils did not differ significantly with time since conversion or soil depth ($p > 0.05$; Supplementary Table S1). The proportion of sand in the soil did not differ significantly with time since conversion ($p < 0.05$; Supplementary Table S1), but there was a significantly greater proportion of sand in the 5–15 cm depth interval (24%) compared with 0–5 cm (20%) ($p < 0.05$; Supplementary Table S1). Regardless of the subtle differences in sand content, soils in the area have a silt loam texture (sand (22% ± 21%), silt (53% ± 16%), clay (25% ± 11%)). There was a significant land conversion by depth interaction effect for WAS, OM , ACE protein, Resp, TN, and TC ($p < 0.05$; Supplementary Table S1). In the 5–15 cm depth, there was no effect of land conversion on any of these indicators ($p > 0.05$; Supplementary Table S2). In the 0–5 cm soils, land conversion had a significant effect on OM, ACE protein, Resp, TN, and TC ($p < 0.05$); the effect on WAS was only significant at $p < 0.10$ (Supplementary Table S2). The forest soils (0–5 cm) had significantly greater WAS (137%), OM (210%), ACE protein (192%), Resp (159%), TN (190%), and TC (220%) than the agricultural soils and there was no difference in the time since conversion on these indicators (Figs. 2 and 3).

Concentrations of POXC and P, and the overall CASH scores, were significantly affected by land conversion irrespective of depth ($p < 0.05$; Supplementary Table S1) and were consistently higher in the forest compared with the agricultural soils (Fig. 4). Time since conversion had no effect on concentrations of P and POXC, or CASH scores (Fig. 4).

Pearson product-moment correlation coefficients were calculated for the indicators to create a correlation matrix (Supplementary Table S4). Of the 171 pairs, only 54 were significantly correlated to each other ($p < 0.05$) and strong correlations ($r > 0.50$) were observed for only 28 pairs. The majority (24) of these pairs were observed between WAS, Mn, TN, TC, OM, ACE protein, Resp, and POXC.

Discussion

Land conversion resulted in a degradation of SH, as indicated by the changes in the indicators and overall scores but the changes were largely in the surface (0–5 cm) and occurred within the first 10 years following conversion. Acton and Gregorich (1995) reported that between 15% and 30% of soil C stocks are lost after the first 10 years following conversion from forest to agriculture in Canada, while Guo and Gifford (2002) indicated that conversion from native forest to cropland declined soil carbon stocks by 42%. Other data suggest that during the first 30 years after the conversion to agriculture, 30%–35% of the total soil carbon stored is lost in the top 7 cm, and even after 30 years these soils continue to be sources of greenhouse gasses (Oertel et al. 2016). Organic mat-

Fig. 2. (A) Organic matter, (B) wet aggregate stability, (C) soil respiration, and (D) autoclave citrate extractable (ACE) protein concentrations in mineral soils (0–5 cm) collected at forest and <10- and >50-year agricultural sites. Bars are mean ± standard error. Significant differences (p < 0.05) are denoted by different letters.

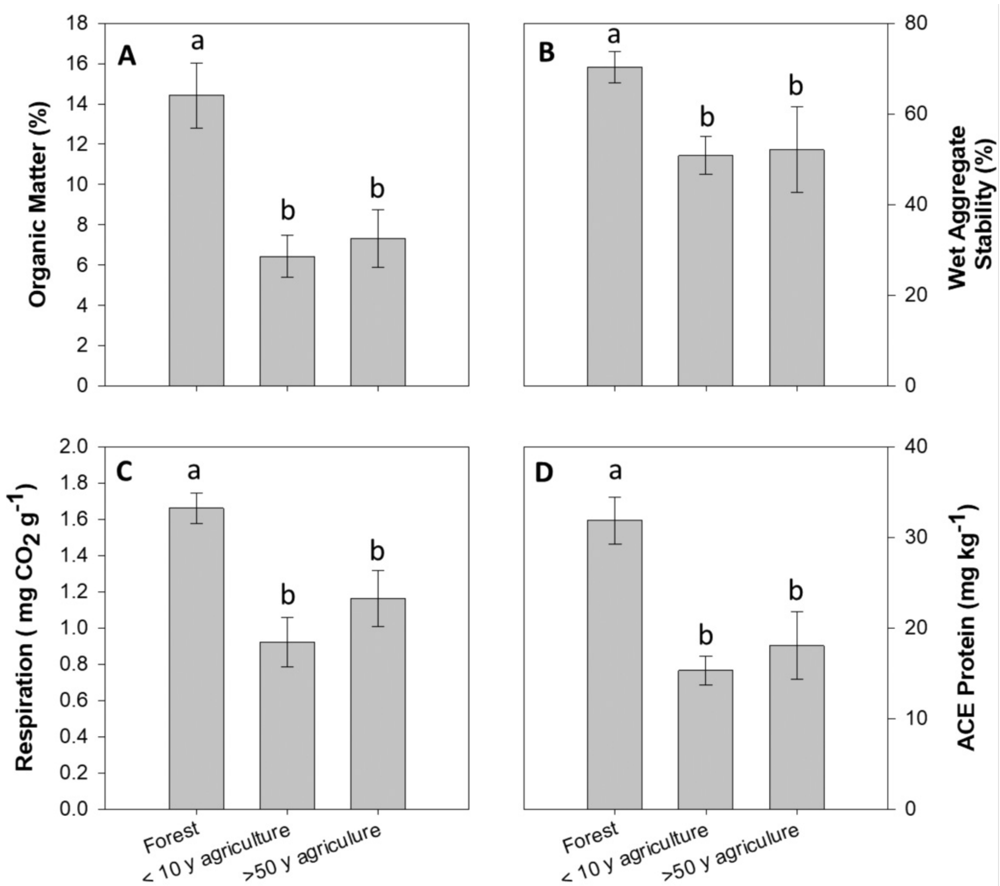
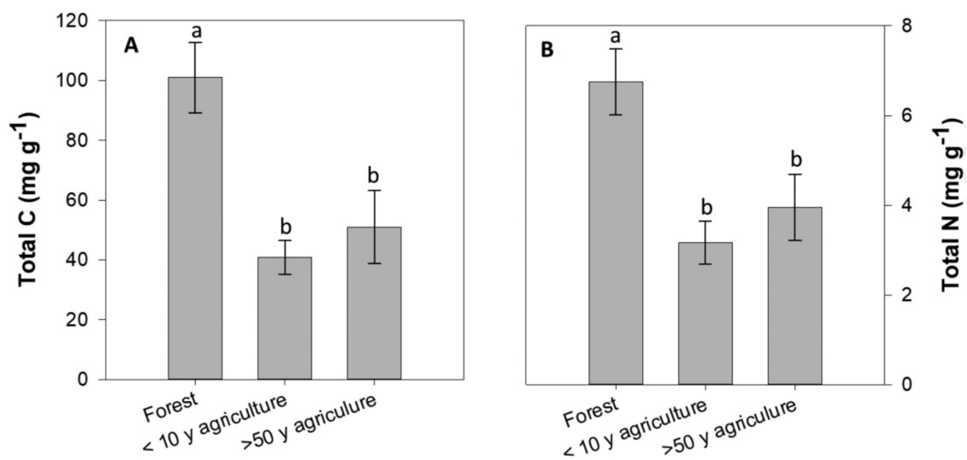


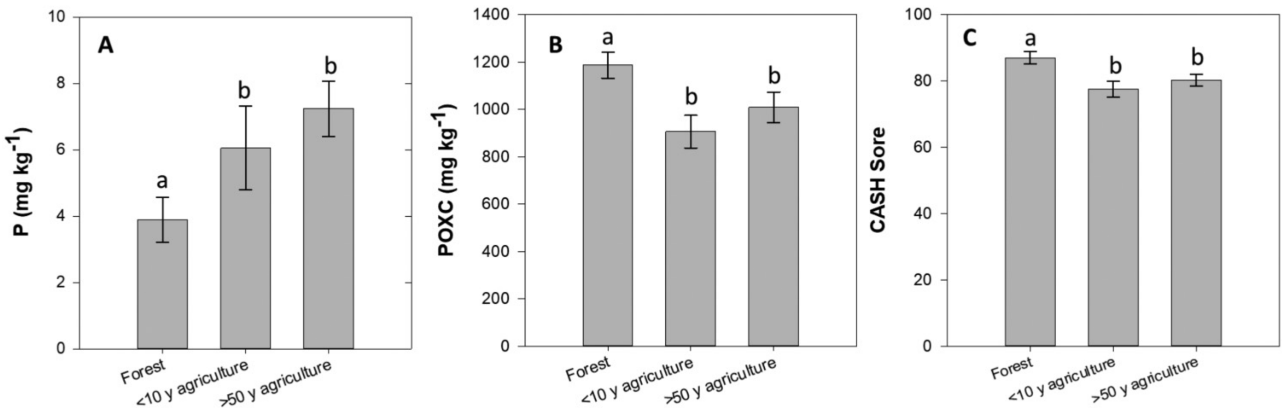
Fig. 3. (A) Total carbon and (B) total nitrogen in mineral soils (0–5 cm) collected at forest sites and <10- and >50-year agricultural sites. Bars are mean ± standard error. Significant differences (p < 0.05) are denoted by different letters.



ter declined from 144 mg/g in the forest to 69 mg/g in the agricultural soils. Declines were also evident in the 5–15 cm depth interval (85–58 mg/g), but the difference was not statistically significant.

The loss of OM is consistent with declines in aboveground and belowground vegetation inputs that accompany most conversions to agriculture (Moebius-Clune et al. 2011). In a forest, belowground dead roots are the primary sources of soil C (Guo et al. 2007), and rapid declines of OM are partly attributable to the loss of OM inputs and partly due to the increased rates of decomposition of existing OM. This is evident in the decline in light-fraction SOM (Post

Fig. 4. (A) Concentrations of phosphorus, (B) permanganate oxidizable carbon (POXC), and (C) Comprehensive Assessment of Soil Health (CASH) scores in mineral soils (0–15 cm) collected at forest sites and <10- and >50-year agricultural sites. Bars are mean ± standard error. Significant differences (p < 0.05) are denoted by different letters.



and Kwon 2000). Also, tillage breaks down soil macroaggregates exposing organomineral surfaces and gives decomposers access to intra-aggregate carbon that lead to high rates of decomposition when combined with increases in soil temperature with forest clearing (Pennock and Van Kessel 1997). Despite these declines, SOM concentrations are higher than in southern Ontario, where SOM concentrations range from 16 to 43 mg/g in agricultural soils (Congreves et al. 2015).

Organic matter influences many soil functions, including the number and species of microorganisms, nutrient cycling, soil structure, soil aggregation, water storage, and infiltration rates (Wall et al. 2012; Cano et al. 2018; King et al. 2020). In this study, OM concentrations were highly correlated with WAS, Resp, and concentrations of TN, TC, ACE protein, and POXC, which is consistent with the findings of Graham et al. (2021) and Fine et al. (2017). Therefore, it is not surprising that all these indicators also declined significantly with land conversion. Wet aggregate stability is an indicator of the soil's ability to resist erosion and WAS declined by 27% in the 0–5 cm depth interval with land conversion. Graham et al. (2021) reported declines in WAS of 7% and 19% in grasslands converted to row crops using no-till and conventional tillage systems, respectively. Tillage breaks up aggregates and exposes OM to oxygen and microbial decomposition (Helfrich et al. 2006), and though there was no significant effect of long-term cultivation on WAS, it was lowest in the agricultural soils that were converted more than 50 years ago. Of note is that surface and subsurface hardness were not affected by land conversion, suggesting that the conservation tillage systems used in the area are not leading to significant soil compaction but that it may be affecting aggregate stability.

Land conversion from forest to agriculture led to significant increases in soil P concentrations (∼59%). These increases are likely driven by organic and inorganic fertilizer inputs but may also reflect the release and retention of P from the rapid decomposition of OM. No other chemical indicators (i.e., pH, K, Fe, Mg, Mn, Zn) were significantly affected by land conversion.

Most of the significant effects of land conversion were detected in the biological SH indicators. Soil proteins are the largest pool of organic N (Weintraub and Schimel 2005) and the ACE protein measurement used in this study is an indicator of potentially available N (Hurisso et al. 2018). Autoclave citrate extractable protein declined by 48% in the near surface (0–5 cm) with land conversion, while TN declined by 38%. Similarly, POXC is used as an indicator of labile carbon availability and is viewed as being a highly sensitive indicator of management induced change. It only declined by 18% while TC declined by 46%. This result may suggest that losses of SOM may be more concentrated in the stable fraction of the SOM pool and that the microbial community may be mining SOM stores for N, which is typically limiting in the soil.

Soil respiration was also lower in the <10-year agricultural soils than in the forest soils and was most strongly correlated with TN, consistent with the tight coupling between the N and C cycles. Other studies show that continued loss in OM leads to lower Resp over time (Moebius-Clune et al. 2017; Yiqi and Zhou 2010), but this study indicated that Resp was comparable between the forest soils and sites that had been in agriculture more than 50 years ago. Litter removal and cultivation usually decreased Resp and increased with input additions (Jonasson et al. 2004), with the influence of an abiotic process such as temperature, precipitation, and evapotranspiration (Yiqi and Zhou 2010, p. 105).

The CASH scores and sensitivity of indicators

The CASH scores were significantly higher in the forest (86) than in the agricultural sites (79) but there was no significant effect of time since conversion suggesting that any deterioration to SH happened quickly but then stabilized. In all cases, these scores are very high to high. None of the chemical indicators showed significant changes with land conversion. The CASH scores were developed for agricultural soils (Moebius-Clune et al. 2017); however, its application in nonagricultural soil also provides an overview of forest sustainability linked to SH. The relevance of the soil indicators in undisturbed soil provides an indicator of soil ecosystem integrity and the ecological functions provided by those ecosystems (FAO 2020).

In addition, determining a benchmark for SH by comparing forests and agricultural fields can be used to support decision-making to improve SH (Maharjan et al. 2020).

Conclusion

Increased knowledge of land-use changes after the conversion from forest to agriculture on SH indicators is important to understand how soil functions. Our study found that land conversion has detrimental effects on physical and biological indicators of the SH and CASH scores. Most of these differences were detected at the surface (0–5 cm).

Land conversion generally resulted in declines in SH indicators and an overall decline in the CASH scores. There were no negative effects of land conversion on the suite of chemical indicators measured in this study, aside from P, but there were detrimental effects on soil physical and biological indicators that are closely tied to declines in SOM. Most of the differences were detected at the surface (0–5 cm) but we acknowledge that this may not be the case for agricultural areas with conventional tillage systems.

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Supplementary material

Supplementary data are available with the article at https://doi.org/10.1139/cjss-2021-0170.

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