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ARTICLE

Aggregate stability after 25 years of organic, conventional, and grassland management

April Stainsby and Martin H. Entz

Abstract: Aggregate stability (AS) was measured in the 25th year of a long-term organic — conventional comparison field study. Located in southern Manitoba, the study includes two, four-year crop rotations under conventional and organic management, plus a grassland. The forage-grain rotation includes alfalfa (*Medicago sativa*)–alfalfa–wheat (*Triticum aestivum*)–flax (*Linum usitatissimum*). The grain only rotation includes wheat–flax–oat (*Avena sativa*)–soybean (*Glycine max*); hairy vetch (*Vicia villosa*) is substituted for soybean in the organic system. Composted manure was added every 4 yr to half of the organic forage-grain rotation to correct a phosphorus deficiency. The wheat and flax phases were sampled at depths (0–10 cm; 10–20 cm) in spring 2017, and wet aggregate stability was measured using the Yoder method with stacked sieves. Mean weight diameter (MWD) was calculated. AS in the organic systems was never lower than that of comparable conventional systems, but had more large aggregates in only a few cases. Our hypothesis that including alfalfa would increase AS was supported in only a few instances. The largest aggregates (1–2 mm and 2–6.3 mm) and the fewest smallest aggregates (0.25–0.5 mm) were observed in the grassland. For the intermediate aggregate size class (0.5–1 mm), the organic forage-grain systems had levels similar ($P > 0.05$) to the grassland. While adding manure increased plant growth by about 40% in the organic forage-grain rotation, no AS differences were observed. Limited AS response in the arable systems may be due to suboptimal soil C contents; only the grassland had a C content above the minimum 35 $g{\cdot}kg^{-1}$ postulated for Vertisols.

Key words: aggregate stability, organic agriculture, perennials, manure, grassland.

Résumé : Les auteurs ont mesuré la stabilité des agrégats (SA) la 25e année d'une étude comparative sur le terrain entre l'agriculture biologique et l'agriculture classique. L'étude, qui s'est déroulée dans le sud du Manitoba, portait sur deux assolements de quatre ans gérés de façon habituelle ou biologique, ainsi que sur une prairie. L'assolement fourrage-grain en était un de luzerne (*Medicago sativa*)-luzerne-blé (*Triticum aestivum*)-lin (*Linum usitatissimum*) alors que l'assolement de grains en était un de blé-lin-avoine (*Avena sativa*)-soja (*Glycine max*). La vesce velue (*Vicia villosa*) remplaçait le soja dans le système biologique. Tous les quatre ans, on a ajouté du fumier composté à la moitié de l'assolement biologique fourrage-grain afin de corriger une carence en phosphore. Le sol a été échantillonné à une profondeur de 0 à 10 cm et de 10 à 20 cm pendant la culture du blé et du lin, au printemps 2017, et on a mesuré la stabilité des agrégats humides selon la méthode de Yoder, grâce à une succession de tamis. Ensuite, les auteurs ont calculé le diamètre moyen pondéré des agrégats. Dans les systèmes organiques, la SA n'est jamais plus faible que celle relevée dans les systèmes agricoles classiques, mais les gros agrégats étaient plus nombreux dans certains cas. L'hypothèse que l'inclusion de la luzerne augmenterait la SA n'a été confirmée qu'à de rares occasions. Les plus gros (1–2 mm et 2–6,3 mm) et les plus petits (0,25–0,5 mm) agrégats ont été observés dans le sol de la prairie. La concentration d'agrégats de taille moyenne (0,5–1 mm) dans le système fourrage-grain biologique était similaire ($P > 0{,}05$) à celle observée dans la prairie. Bien que l'addition de fumier améliore la croissance des plantes d'environ 40 % dans l'assolement fourrage-grain biologique, aucune variation n'a été notée pour la SA. La faible réaction de la SA dans les systèmes arables pourrait venir d'une concentration de C inférieure à la concentration optimale, car la prairie était la seule à contenir plus que les 35 g de C par kg de sol postulés pour les vertisols. [Traduit par la Rédaction]

Mots-clés : stabilité des agrégats, agriculture biologique, vivaces, fumier, prairies.

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Introduction

Improving soil health has become an important focus worldwide as a way to build resilient agricultural systems. Aggregate stability (AS) is an important measure of soil health as it relates to many soil physical and biological functions (Six et al. 2004). A well-structured soil with stable aggregates creates pore networks in the soil that improve water infiltration and aeration as well as root growth (Tisdall and Oades 1982). Well-aggregated soils are less susceptible to compaction, and stable aggregates on the surface reduce the risk of erosion and surface crusting. Aggregates also physically protect organic materials from decomposition, which increases their residence time in the soil; hence aggregates are important sites of carbon storage (Six et al. 2004; Helgason et al. 2010).

Our first question was whether wet aggregate stability would be different in organic vs conventional crop production after 25 yr. Previous long-term organic-conventional comparison studies have provided an important resource for comparing soil physical properties including aggregate stability. For example, in the long-term DOK trial in Switzerland (Mäder et al. 2002), soils under organic management had lower susceptibility to erosion than those managed conventionally (Siegrist et al. 1998); aggregate stability ranked biodynamic > organic > conventional with manure > conventional with mineral fertilizer. A 70-yr study comparing biodynamic and conventional production in the Netherlands showed higher mean weight diameter (MWD), a greater proportion of large aggregates, and greater water stable aggregates in organic and permanent pastures compared with conventional cropping (Pulleman et al. 2003). The differences were observed in both 0–10 cm and 10–20 cm soil depths. Given this, our first hypothesis was that long-term organic management would have a higher MWD and larger aggregates than conventionally managed soils.

Some of the aforementioned organic-conventional comparison studies (e.g., DOK trial; Rodale, USDA Beltsville) use large amounts of animal manure to fertilize the organic or biodynamic systems. For example, in the Pulleman et al. (2003) study, 10 $Mg \cdot ha^{-1} \cdot yr^{-1}$ of farm yard manure (FYM), plus 10 $t \cdot ha^{-1} \cdot yr^{-1}$ of slurry during the grass pasture, was added to the biodynamic system. Given the central role of large manure additions in the success of many organic production systems, a second question in our research was how additions of manure would affect aggregate stability in a long-term organic system. Increased slaking-resistant macroaggregates (250–1000 μm) were observed after 18 yr of manure application in a Quebec study (Aoyama et al. 1999). This effect was primarily a result of the organic matter (OM) added by the manure, a relationship that was studied decades earlier by Tisdale and Oades (1982). In contrast to the manure, NPK fertilizer did not affect soil OM level or macroaggregation (Aoyama et al. 1999). In an Alberta study, on the other hand, Whalen and Chang (2002) observed fewer water stable aggregates in long-term manure amended land compared with unmanured land and attributed these results to destabilizing dispersing agents in the manure.

However, the reality is that most dryland Prairie organic grain producers do not add large amounts of animal manures. For example, in a survey of 60 Saskatchewan organic farms, Knight et al. (2010) reported that use of manure on organic farms was relatively rare, and rock phosphate was the most popular P source. The authors concluded that low manure use on Saskatchewan organic farms "is probably indicative of the large farms in the Canadian Prairies having more land area than manure available to apply to the land". This lack of manure use on Prairie organic farms was underscored in a recent survey of green manure crops in 41 organic fields in Manitoba and Saskatchewan (Thiessen Martens et al. 2019). Green manure plant tissue P concentration was 2.1 $g \cdot kg^{-1}$, with values ranging from 0.8 to 3.9 $g \cdot kg^{-1}$. About half of all green manures had P concentrations below the critical value of 2.0 $g \cdot kg^{-1}$ established for forage crops (Kelling and Matocha 1990); most of these were grown on soils with very low available P. This observation underscores the potential P deficiency in organic grain production systems (Knight et al. 2010). Therefore, an additional question in our research was how addition of perennial hay crops, unfertilized, would affect AS in organic production. Could lack of nutrients in unmanured organic forage-based rotations result in lower AS?

Most studies of AS in organic agronomic research have involved arable systems. One exception is the North Carolina State University's "Farming Systems Research Unit" trial, started in 1998. It is interesting because, in addition to 3 yr organic and conventional rotations, it includes a 15 yr crop and livestock rotation with annual crops and perennial pastures, plantation forestry plots, and fields that have been left to natural succession processes (Mueller et al. 2006). In the first 5 yr they found that AS, based on sieving dry aggregates through a nest of sieves, was higher in the crop/livestock and natural succession fields than in the organic and conventional systems. The organic system had the lowest bulk density, whereas the crop/livestock system had the highest, which they attributed to compaction from animals and lack of tillage (Mueller et al. 2006). In southern Manitoba, the Glenlea study contains a restored grassland treatment where native grass mixtures have been growing since 1993. This grassland has markedly increased C content in the 0–120 cm soil profile compared with all arable systems, including those that include short-term perennials (Bell et al. 2012). It was interesting, however, to observe similar levels of microbial biomass carbon (MBC), soil respiration, and qCO_2 (microbial metabolic quotient) in the forage-grain rotations and the long-term grasslands (Braman et al. 2016). Therefore, an additional objective of the present study was to compared AS between arable rotations and the grassland benchmark system. We hypothesized that these grassland plots would have more large aggregates.

The response of AS to beneficial management practices can be strongly influenced by soil type. For example, an Argentinian study showed that soil organic carbon (SOC) was a major determinant of AS in a Molisol, but less so in a Vertisol. This distinction is relevant in the present study since soils at Glenlea are Vertisols. In many soils, SOC is a major agent responsible for stabilizing aggregates (Novelli et al. 2013). But there is evidence to suggest that SOC may be more important to AS in Molisols than in Vertisols (Novelli et al. 2013). On the other hand, in India, application of distillery effluents increased the wet aggregate stability of the Vertisol through enhanced soil organic carbon as well as the aggregate associated carbon (Biswas et al. 2009).

In addition to the aforementioned hypotheses and research questions, we were interested in comparing what we deemed the most "soil friendly" organic system with a representative cropping system in the region (i.e., the grain-only rotation with NPK fertilizer and pesticides added). Therefore, a separate analysis was conducted where the manured organic forage-grain rotation was compared with the conventional grain only system.

Methods

Study site

This study took place at the Glenlea Long-term Rotation, at the University of Manitoba's Glenlea Research Station, south of Winnipeg, Manitoba (49°38′25″N, 97°8′28″W; 230 m above sea level). The long-term field study was established in 1992 on Gleyed Humic Vertisols (Bell et al. 2012) of the Scanterbury and Red River series and Gleyed Black Chernozems of the Hoddinott series (CANSIS, n.d.). These heavy clay soils (71% clay, 23% silt, and 6% sand in the top 18 cm) in the Red River Valley have 2.59 $g{\cdot}kg^{-1}$ organic carbon and a pH of 6.5 in the top 18 cm (Bell et al. 2012). The Glenlea Long-term Rotation compares organic and conventional management, with two crop rotations under each management system. The study has a completely randomized design, rotations are fully phased, and there are three replicates. Each main plot is 4 × 28 m in size. The organic and conventional plots have been managed as such continuously since 1992, while the current 4 yr rotations have been in place since 2004; details of study design changes are described by Carkner et al. (2020). The annual "grain-only" rotation consists of wheat–flax–oat–soybean. Hairy vetch/barley (*Hordeum vulgare* L.) green manure is substituted for soybean in the organic version of the grain-only rotation. The "forage-grain" rotation consists of alfalfa–alfalfa–wheat–flax. The forage consists of alfalfa mixed with timothy (*Phleum pratense* L.), orchardgrass (*Dactylis glomerata* L.), and red clover (*Trifolium repens* L.). Forages are seeded in early spring of the first "forage year". Since 2007 composted cattle manure has been added once every 4 yr to half of each main plot in the organic forage-grain rotation only. The manure is applied based on a combination of amount of phosphorus removed in crop product and the amount of phosphorus recommended by soil tests and is approximately 80 kg $P{\cdot}ha^{-1}$ every 4 yr. We estimated total C additions from manure at 3.9 $Mg{\cdot}ha^{-1}$ based on Larney et al. (2006). The conventional plots receive inorganic N and P annually based on soil test results. The soil of all plots was rotovated in the fall of each year, usually once but sometimes twice, and rotovated and then harrowed prior to seeding in the spring. The rotovator, while not an ideal tool for maintaining soil health, was selected to reduce the risk of moving soil out of plots (D. Lobb, U of M, personal communication).

Briefly, crop management consisted of seeding in springtime, fertilization at the time of seeding (conventional plots only), harvesting alfalfa two times during the season, and harvesting grain crops with a plot combine, leaving straw in the field. Weeds in the conventional plots were controlled with postemergence herbicides applied several weeks after crop emergence. In the organic grain crops, a wheel hoe was used to control weeds growing between the rows. Replicated restored grassland plots at the site serve as a benchmark. A mixture of native grasses was planted in 1993. Plant residue was burned every 4–5 yr (in early spring). Details of land management, native species used, and soil and climate data are given in Bell et al. (2012) and Braman et al. (2016). Biomass production and grain yields have been reported elsewhere (e.g., Carkner et al. 2020).

Plant productivity

Net primary productivity for the above ground was measured each year in the study. Prior to crop harvest, the crop and weed biomass was determined from random ¼ m square samples taken in two places within each experimental unit. The material was dried at 60 °C to constant dry weight (usually 48 hours) and weighed.

Soil sampling procedures

Sampling for aggregate stability occurred in the spring, just prior to tillage and seeding (3–6 May and 9–11 May 2017). Grassland plots were sampled later (9 June and 11 June) because the heavy clay soil was too wet to sample in May. Soil cores were taken following the wheat and flax phases only. Samples were taken at 0–10 cm and 10–20 cm depths. These depths were chosen because the soil was tilled to approximately 10 cm, and therefore both tilled soil and soils below the till layer could be analyzed. Four samples were taken per 4 × 28 m plot, using a 6 cm diameter hollow soil corer. As the soil was very hard, a sledge hammer was used to push the core into the ground, and the core was dug out with a shovel. Samples were carefully removed from the corer and placed in large flat-bottomed paper bags, which were transported in a single layer on trays. This was done to avoid disturbing the aggregates. Subsamples were carefully broken up by hand, passed through a 6.3 mm sieve, and then air dried before being stored. Bulk density samples were taken at the middle of 0–10 cm and 10–20 cm depths using hollow rings (core volume 50.64 cm^3).

Soil analysis

Wet aggregate stability was determined by wet sieving using a Yoder type wet sieve shaker (Yoder 1936). Stacks of five sieves with mesh diameters of 0.25, 0.5, 1, 2, and 4.75 mm were used following the methods in Angers and Mehuys (1993) for size distribution of water-stable aggregates. These are all considered macroaggregates, as they are greater than 0.25 mm in diameter. Forty grams of soil was placed on the top sieve, which was under about 0.5 cm of water, and once the soil was fully wetted, sieving was initiated. The sieves moved vertically a distance of 10 cm at a rate of 32 oscillations per minute for 10 minutes. After sieving, samples were washed into pre-weighed jars, dried at 105 °C for 48 hours, and then weighed. MWD, a measure of the size distribution of water-stable aggregates, was calculated using the following formula:

$$\mathrm{MWD} = \sum_{i=1}^{n} x_i \mathrm{WSA}_i$$

where x_i is the mean diameter of size fraction $_i$ and WSA_i is the proportion of aggregates retained on sieve $_i$ (Angers and Mehuys 1993).

Bulk density samples were weighed immediately after collection, oven dried at 60 °C until they reached constant weight, and then weighed to determine the mass for bulk density.

Statistical analysis

Analysis of variance for aggregate stability data was performed using PROC MIXED in SAS 9.4 (SAS Institute Inc. 2016), with the study as a completely randomized design. The univariate procedure was used to test normal distribution of data and residuals. The repeated/group = statement was used to account for heterogeneity of variance of the residuals, with group being the factor with the lowest Akaike information criterion value. If assumptions of the ANOVA were not met, data were log10 transformed. Treatment was a fixed factor, and there were no random factors. There were a total of six treatments: (1) grain-only organic; (2) grain-only conventional; (3) forage-grain organic; (4) forage-grain organic with manure; (5) forage-grain conventional; and (6) grassland. Each crop and depth combination was analyzed separately because the intent of the study was to compare the effects of the treatments on AS within each crop type and depth, not to see the effects of crop type and depth on AS. The Tukey–Kramer post-hoc test was used for means separation with an alpha value of 0.05 as a significance level.

As an additional test, to increase the number of experimental units in the analysis to get a better estimate of experimental error, and to confirm the previous analysis, an ANOVA that combined the two crop types (grain-only and forage-grain) and depths was also done. The analysis involved the same treatments (see previous paragraph) except the fixed factors crop (two levels) and depth (two levels) were added to the model, and the grassland treatment was removed. This model showed no effect of treatment on MWD. When there was an effect of the treatments on individual size classes, it was very similar to the results when the crops and depths were analyzed separately. This showed that analyzing the data from both crop years and depths together, and thereby increasing the number of experimental units, did not change the results.

Three single degree of freedom a priori contrasts were done, with treatments and crop type as fixed factors, and the two depths were analyzed separately. The contrasts corresponded to the first three hypotheses of the present study and compared the grain-only organic with forage-grain organic treatments; the forage-grain organic no manure with the forage-grain plus manure treatment; and the forage-grain manure treatment with the grain-only conventional treatment. For the final contrast, the forage-grain organic plus manure treatment (deemed the best organic treatment in terms of agronomic performance) was contrasted with the grain-only conventional system (deemed as the treatment most similar to standard practices in the region).

Analysis of variance for proportion data (i.e., percent of total soil mass in any one aggregate size class) was done using GLIMMIX with a beta distribution. Treatment was the fixed effect, and there were no random effects. The treatments were the same as above, and the two crop types and depths were analyzed separately so that the grassland treatment could be included in the model. The Laplace method was used to run the model with the ccll link function because it gave the Chi square value closest to 1. Again, the Tukey–Kramer procedure was used for means separation with an alpha value of 0.05.

Results

Bulk density

The grassland had higher bulk density (BD) than the forage-grain conventional and forage-grain organic treatments in the wheat phase at 0–10 cm depth (Table 1). Though they were not significantly different, the three forage-grain treatments had notably lower BD than the annual grain treatments, ranging from 10% to 24% lower. In the flax phase of the rotation, at 0–10 cm depth, there were no significant differences in BD, though again the forage-grain treatments had notably lower BD than the annuals. At 10–20 cm depth in both crop phases, the grassland had lower BD than the annual conventional treatment. Our results differ from Mueller et al. (2006), who observed lower bulk density in organic systems.

Mean weight diameter

MWD of water stable aggregates was similar among arable treatments for both depths in the wheat phase and in the top 10 cm in the flax phase of the rotation (Fig. 1). The grassland plots had much higher MWD than all arable treatments except in the 10–20 cm depth of the flax phase, where MWD in all three forage-grain treatments (conventional, organic, and organic + manure) was statistically similar to the grassland. The two grain-only treatments (conventional and organic), on the other hand, had lower MWD than the grassland in the 10–20 cm soil depth of flax.

MWDs in the organic grain-only and organic forage-grain treatments were compared using a priori contrasts to discern the effect of forage within an organic rotation (data in Fig. 1). At the 0–10 cm depth, there was no difference between systems. However, at the 10–20 cm depth, the organic forage-grain system had 15% higher MWD than the organic grain only system ($P = 0.0260$), demonstrating an advantage to including short-term alfalfa phases in organic production. Organic forage-grain plots with and without manure were also compared. At both depths there was no effect of manure on MWD. Finally, the most productive organic cropping system in the study, forage-grain with manure added, was compared with the conventional grain-only system, deemed the commercial standard. The contrasts showed no significant differences in MWD between the two systems.

Individual aggregate size classes

MWD may mask changes in individual size categories, as different combinations of numbers can give the same MWD. Therefore, aggregate size classes were analyzed individually to better understand what fractions of the soil were being affected by management treatments. The four aggregate size classes were: 0.25–0.5 mm (termed smallest); 0.5–1 mm (termed small); 1–2 mm (termed intermediate); and 2–6.3 mm (termed large). The general trend was that the grassland had fewer smallest aggregates (0.25–0.5 mm) and more intermediate and large aggregates (1–2 mm and 2–6.3 mm) than the arable crop treatments (Figs. 2 and 3). At the 10–20 cm soil depths for both wheat and flax, all treatments, including the grassland, had a similar mass of small aggregates (0.5–1 mm).

Differences were observed between treatments in the 0–10 cm soil depth. In the wheat phase, the mass of small aggregates (0.5–1 mm) ranked grain-only > the two forage-grain organic treatments > the grassland treatment; each significantly different from each other (Fig. 2). In the 0–10 cm depth of the flax phase, both conventional treatments (grain-only and forage-grain) had significantly more small aggregates than the organic forage-grain plots (with and without manure). Therefore, surface soil results from both wheat and flax show an advantage for the organic forage-grain systems over the two conventional systems because a lower mass of small aggregates was observed.

Table 1. Bulk density ($g{\cdot}cm^{-3}$) in treatments at Glenlea long-term rotation in the wheat and flax phases of the rotation at two depths.

	Wheat		Flax	
	0–10 cm	10–20 cm	0–10 cm	10–20 cm
Ann Con	0.96ab	1.17a	0.88a	1.22a
Ann Org	0.88ab	1.11ab	1.02a	1.17ab
Per Con	0.79b	1.04ab	0.78a	1.07ab
Per Org	0.76b	1.07ab	0.76a	1.06ab
Per Org M	0.73ab	1.04ab	0.79a	0.99ab
Grassland	1.07a	0.93b	1.07a	0.93b

Note: Letters indicate statistical significance using the Tukey test for means separation with alpha = 0.05. Ann Con stands for the annual conventional grain rotation, Per Con for the conventional forage-grain rotation, Ann Org for the organic annual grain rotation, Per Org for the organic forage-grain rotation, Per Org M for the organic forage-grain rotation with manure added, and Grassland for the grassland/prairie plots.

Aggregates in the 2–6.3 mm size class were considered large aggregates. At 10–20 cm, the arable treatments and the grassland were more similar to each other for mass of large aggregates. In fact, for flax, all treatments, including the grassland, were similar to each other (Fig. 3). This contrasted with results for wheat where all treatments were similar to the grassland except for the grain-only conventional, which had fewer large aggregates than the grassland but was similar to the other treatments (Fig. 2). When the large aggregate fraction was assessed on a proportional basis, the forage-grain organic treatment with manure in wheat (0–10 cm) was superior to both conventional treatments (grain-only and forage-grain rotations) (Table 2). This result pointed out an advantage for the organic forage-grain system over both the conventional grain-only and the conventional forage-grain systems.

Discussion

Organic vs conventional systems

Overall, few AS differences between organic and conventional management were detected. Where differences were observed, the trend was for some organic systems to have fewer small aggregates and in one case the proportion of large aggregates was greater in the forage-grain organic than in the forage-grain

Fig. 1. Mean weight diameter (MWD) of stable aggregates in treatments at Glenlea long-term rotation in the wheat and flax phases of the rotation at two depths. Ann Con stands for the annual conventional grain rotation, Per Con for the conventional forage-grain rotation, Ann Org for the organic annual grain rotation, Per Org for the organic forage-grain rotation, Per Org M for the organic forage-grain rotation with manure added, and Grassland for the grassland/prairie plots. Letters indicate significance at alpha = 0.05. The Tukey–Kramer post hoc test was used, and error bars represent one standard deviation on either side of the treatment mean.

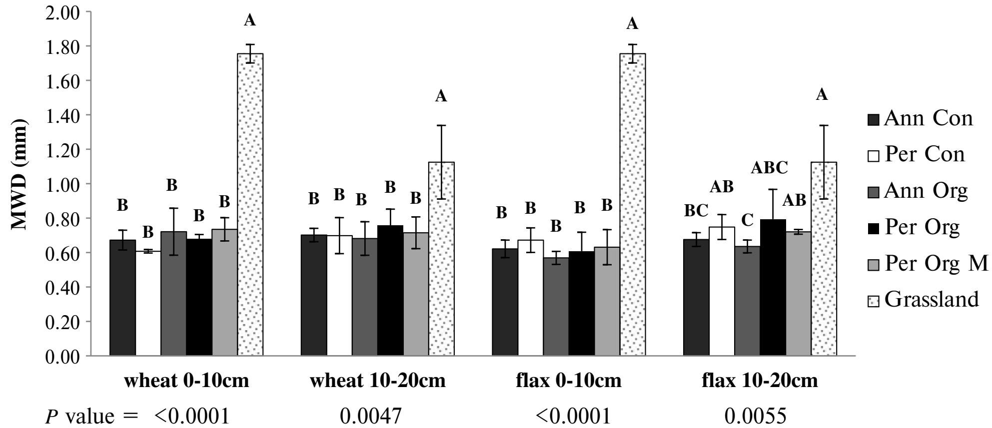


Fig. 2. Stable aggregates (g) in individual size classes in treatments at two depths at Glenlea in wheat plots. Ann Con stands for the annual conventional grain rotation, Per Con for the conventional forage-grain rotation, Ann Org for the organic annual grain rotation, Per Org for the organic forage-grain rotation, Per Org M for the organic forage-grain rotation with manure added, and Grassland for the grassland/prairie plots. *P* value = 0.05. Error bars represent one standard deviation on each side of the mean.

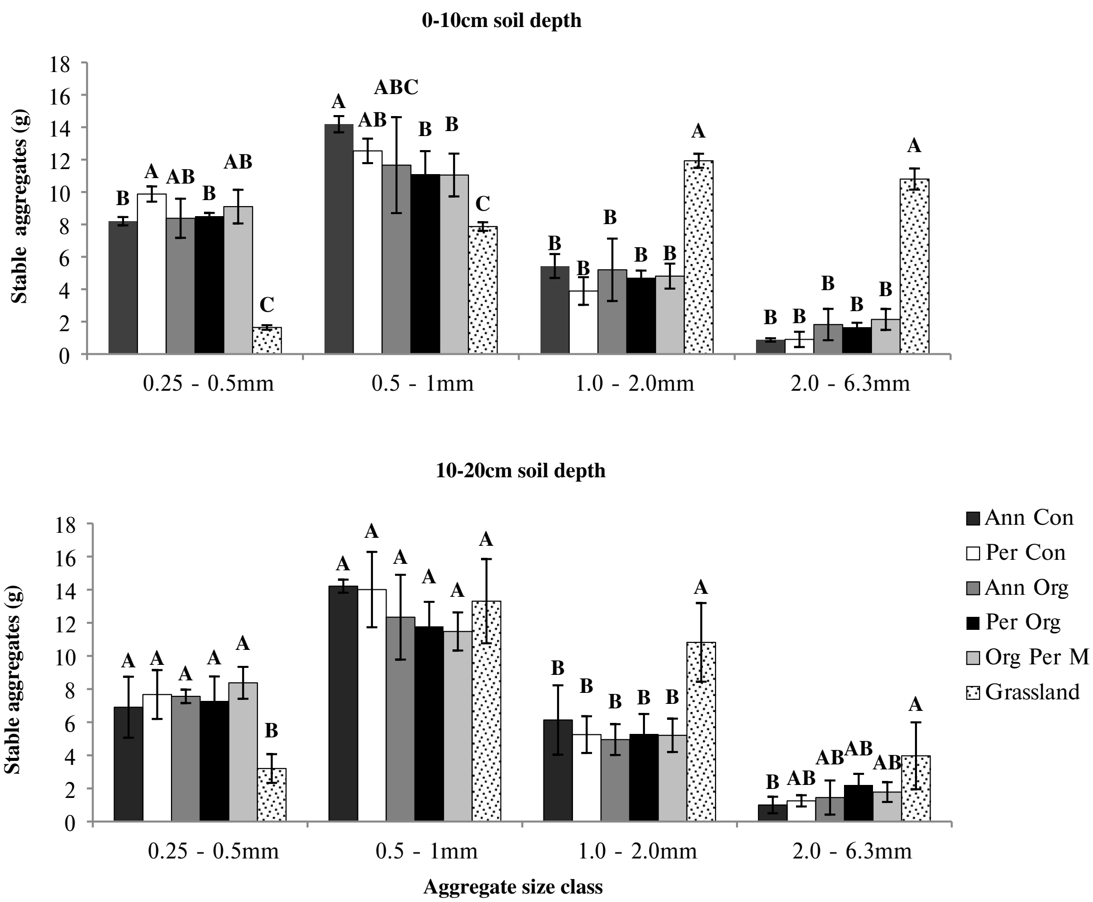
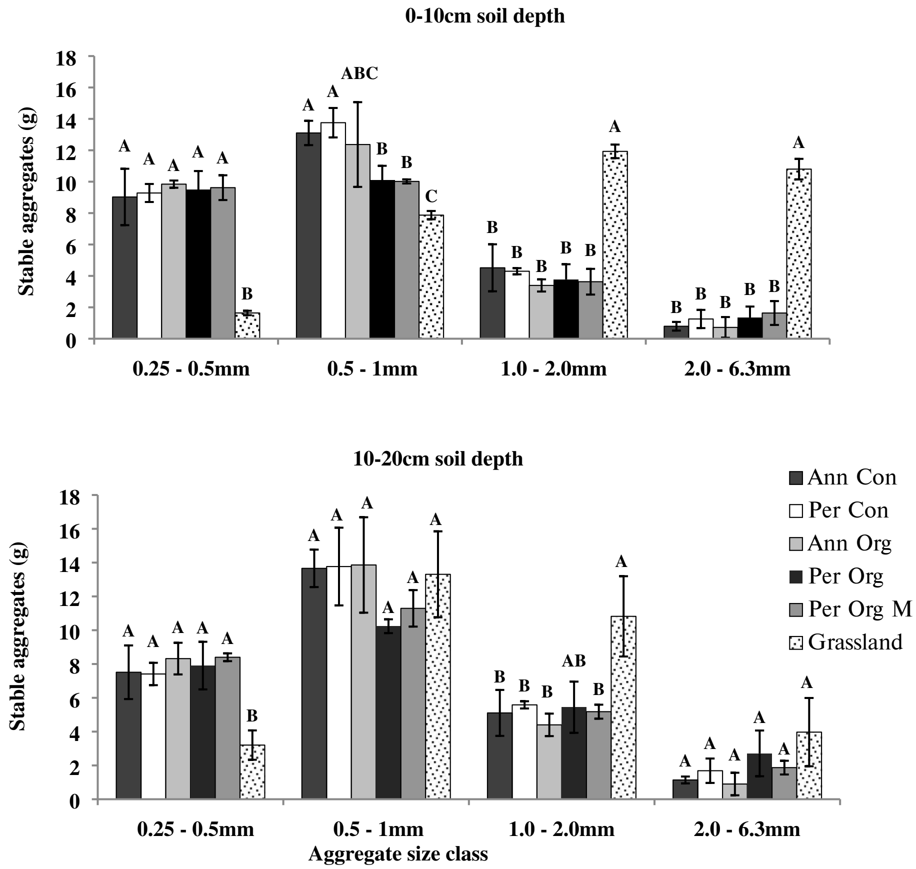


Fig. 3. Stable aggregates (g) in individual size classes in treatments at two depths at Glenlea in flax plots. Ann Con stands for the annual conventional grain rotation, Per Con for the conventional forage-grain rotation, Ann Org for the organic annual grain rotation, Per Org for the organic forage-grain rotation, Per Org M for the organic forage-grain rotation with manure added, and Grassland for the grassland/prairie plots. Error bars represent one standard deviation on each side of the mean.



conventional system. Organic plots at Glenlea also recorded higher levels of mycorrhizal colonization (Entz et al. 2004) and spore diversity (Welsh 2007), which should improve aggregate formation (Helgason et al. 2010). It is worth noting that within the two rotations, there were no instances where the organic system performed worse than its conventional counterpart.

Did adding short-term alfalfa improve AS?

Differences in AS among arable systems observed in this study tended to be between grain-only and forage-grain rotations rather than between organic and conventional management. Evidence for greater AS in the forage-grain rotation was observed for individual aggregate size classes (more small aggregates in grain-only rotations) and for MWD in only one instance (flax at 10–20 cm); in this case all three forage-grain treatments were similar to the grassland while grain-only rotations were lower. One explanation is that the forage-grain rotation had more live roots days due to its perennial growth and less soil disturbance from tillage.

Table 2. Percent of total soil in aggregates in the 2–6.3 mm size class in treatments at Glenlea long-term rotation at two depths and phases of the rotation.

	Wheat		Flax	
	0–10 cm	10–20 cm	0–10 cm	10–20 cm
Ann Con	2.17c	2.50b	1.98b	2.85b
Per Con	2.26c	3.13b	3.14b	4.22Ab
Ann Org	4.54bc	3.63b	1.80b	2.25b
Per Org	4.12bc	5.50ab	3.38b	6.78ab
Per Org M	5.34b	4.45ab	4.09b	4.68ab
Grassland	27.00a	9.93a	27.00a	9.93a

Note: Letters indicate statistical significance using the Tukey–Kramer test for means separation with alpha = 0.05. Ann Con stands for the annual conventional grain rotation, Per Con for the conventional forage-grain rotation, Ann Org for the organic annual grain rotation, Per Org for the organic forage-grain rotation, Per Org M for the organic forage-grain rotation with manure added, and Grassland for the grassland/prairie plots.

Both factors are positively linked to AS (Six et al. 2004; Helgason et al. 2010, respectively). A second reason may be improved soil biology. Sparling et al. (1992) and Hurisso et al. (2013) observed a positive correlation between AS and MBC. Working at Glenlea, Braman et al. (2016) observed higher MBC in the two organic forage-grain systems, compared with the conventional forage-grain or conventional grain-only rotations.

Results of the present study support the positive role than alfalfa can also play in improved soil physical attributes. For example, contrast analysis showed a 15% increase in MWD in organic forage-grain compared with the organic grain-only system ($P = 0.0260$).

Explanations for the modest forage effect in the present study may be related to the choice of the alfalfa-dominant perennial crop or to the short duration of the crop. Oades (1993) reported superior aggregate formation with grasses due to their fine roots, which dry the soil more evenly, resulting in many small cracks in many directions. Rillig et al. (2002) found that grasses increased AS more than a legume or forb species, while Materechera et al. (1992) found that ryegrass (*Lolium rigidum* Gaudin) had the greatest effect on AS followed by wheat and then pea (*Pisum sativum* L.). On the other hand, 2–5 yr of alfalfa have been shown to improve AS (Williams et al. 2017; Guo et al. 2010; Su et al. 2009; Angers 1992). Guidi et al. (2017) found that 1 yr of alfalfa improved AS in degraded soils but not in less degraded soils. By most measures, the soils at Glenlea would not be considered degraded and may therefore be less responsive in terms of AS to additions of perennial crops.

Did adding composted manure improve AS within the perennial organic system?

The role of manure in increasing AS is well documented in organic and tilled systems (Romano et al. 2017; Williams et al. 2017) and when compared with inorganic fertilizer (Pulleman et al. 2003; Ozlu and Kumar 2018). The Glenlea study provided the opportunity to ask this question since manure has been added to the organic forage-grain since 2007, and manure had a large positive effect on net primary productivity of grain (Fig. 4) and forage (Fig. 5) crops. Further, the fact that the unmanured organic forage-grain system is P-deficient (Welsh et al. 2009; Bell et al. 2012; unpublished) allowed us to compare a P-sufficient manured organic system with one that was P-deficient. This is an especially relevant question given the P deficiencies recently documented for eastern Prairie organic farms (Thiessen Martens et al. 2019).

However, unlike previous reports (e.g., Aoyama et al. 1999), our study showed no difference in AS between manured and unmanured forage-grain plots. While the amount of C contributed by manure itself was small (3.9 $Mg \cdot ha^{-1}$), the manured treatment produced much more plant biomass (Figs. 4 and 5) and had higher levels of plant available P (Bell et al. 2012; Carkner et al. 2020). One explanation for the lack of a manure effect may be that soil was sampled two and 3 yr after the most recent manure application (i.e., manure applied in fall of first alfalfa year, but we sampled wheat and flax crops). Wortmann and Shapiro (2007) found that manure increased stable macroaggregates (>0.25 mm) and decreased microaggregates (<0.25 mm), but also that its effect on AS was not detectable 4 yr after manure application.

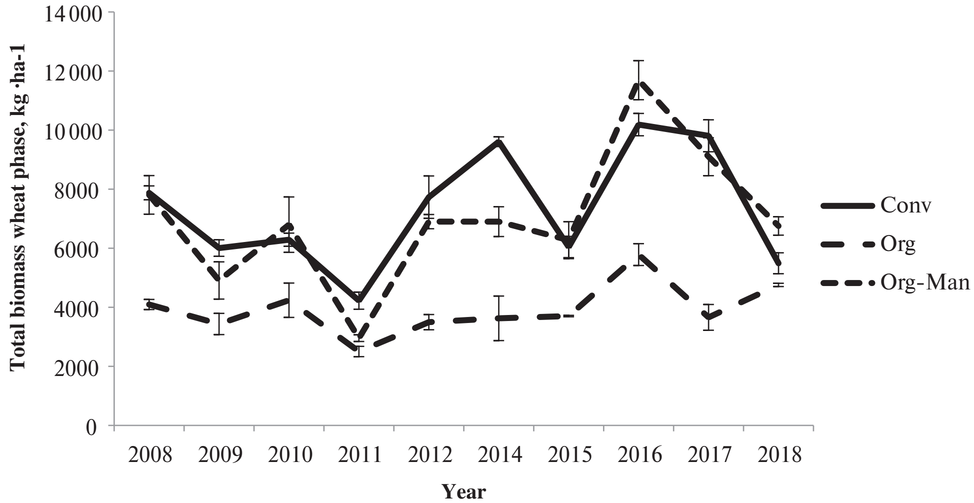
Comparing the best organic with the commercial standard cropping system

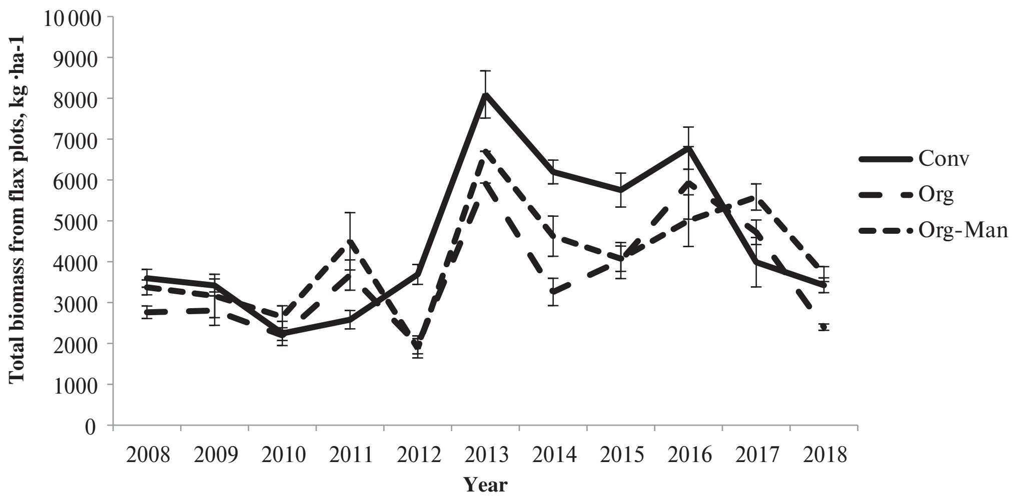
Organic grain production systems that include perennial forages in rotation and receive supplemental nutrients from manuring are considered optimum organic cropping systems (Knight et al. 2010). The Glenlea rotation provided the opportunity to compare such a high functioning organic system with a commercial standard for the region. Results of this comparison showed an AS advantage for the organic system; it had significantly fewer small aggregates in the 0–10 cm soil depths for both wheat and flax (Figs. 2 and 3) and experienced a larger proportion of large aggregates in the 0–10 cm depth for wheat than the conventional standard (Table 2).

Among the possible reasons for AS improvements in the organic compared with the conventional system here, perhaps the strongest contributor may be the addition of a 2-yr forage crop (Angers 1992). Significant AS improvements with the addition of the perennial phase have been previously discussed in our paper. Data from this study appears to rule out manure as a possible explanation for improved AS in the organic system, though the effect of manure was tested only in the forage-grain and never the grain-only rotation. A third possible reason may relate to plant diversity. While the two systems that we compared each contained multiple crops (four for the conventional and three for the organic), the organic system also contained many different annual and perennial weeds, and these weeds could have contributed to AS improvements. Kubota et al. (2015) observed that weeds are important determinants of arbuscular mycorrhizal fungi proliferation in wheat managed organically in Alberta. Greater weed abundance and diversity have been observed in the organic systems at Glenlea (Carkner et al. 2020) and coincided with higher levels of mycorrhizal colonization in flax (Entz et al. 2004) and soil arbuscular mycorrhizal fungi spore diversity (Welsh 2009).

The organic-conventional comparison discussed above involved changes in crop rotation, pesticide use, and manure management, but involved similar tillage regimes in the organic and conventional systems. Future studies should compare organic tilled systems with conventional no-till systems.

Fig. 4. Total aboveground biomass production at time of grain harvest in the wheat (upper) and flax (lower) plots in the forage-grain rotation in conventional, organic (no manure), and organic (with manure) systems.





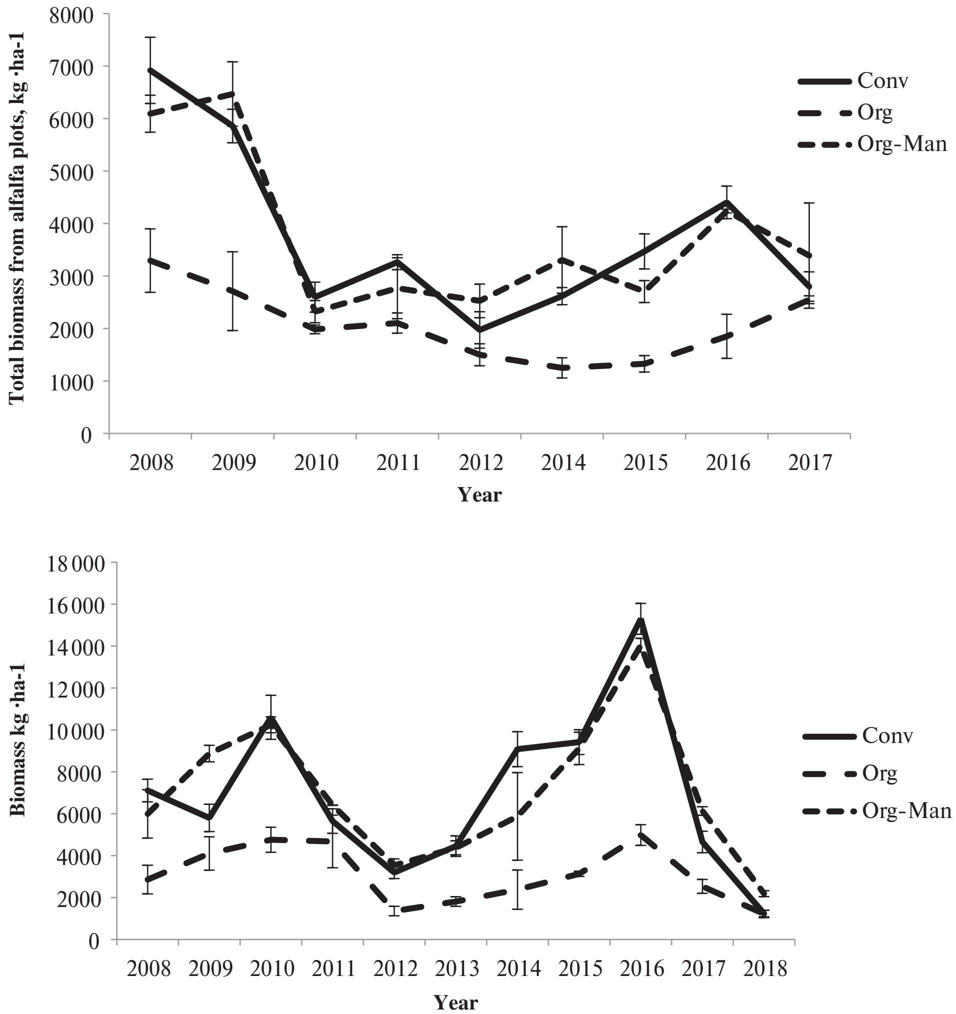
Grassland as benchmark for soil AS

The grassland in this study serves as a benchmark for soil health. As would be expected (Oades 1993), it had a much higher MWD than the arable treatments, fewer small aggregates, and more large aggregates (Fig. 2 and 3). Many studies have found higher AS under long-term perennial grasslands than under annual crops (Sparling et al. 1992; Vezzani et al. 2018). Hebb et al. (2017) observed higher AS in native grasslands than planted pastures; our grassland falls into the latter category.

Root carbon is known to have a longer residence time in the soil (Kong and Six 2010), and organic compounds from roots, both residues and exudates, are important in aggregate formation and stabilization (Six et al. 2004). Roots and associated hyphae are also important in forming larger aggregates through physical entanglement (Six et al. 2004). Older grasslands have been found to have more root biomass than younger grasslands or annually cropped soils (Acharya et al. 2012). The same grasslands at Glenlea also have higher SOC stocks than the arable treatments (Bell et al. 2012).

Plant roots dry out the soil immediately surrounding the roots more quickly than areas without plant roots, causing uneven drying of the soil. When plants are growing in rows, a stronger drying effect within the rows than between the rows causes cracking between, and parallel to, the rows. Whereas in a densely broadcasted stand of pasture, such as the Glenlea grassland plots, the plants and roots are more evenly spread out, causing smaller cracks in many directions as they dry (Oades 1993). This gives the soil a more consistent coarse granular soil structure (Oades 1993). Thus, the arrangement of plants can affect aggregation, and this would at least partly explain the better aggregation in the grasslands compared with all of the arable treatments.

Fig. 5. Total aboveground biomass production for alfalfa in the first year of production (upper) and second year of production (lower) in the forage-grain rotation in conventional, organic (no manure), and organic (with manure) systems.



Soil type influence

One explanation for the modest effect of arable treatments on AS in this study could be the relative importance of physical processes compared with management factors (e.g., increased plant growth providing organic binding agents) on aggregate formation and stabilization in heavy clay soils (Oades 1993). In heavy clay soils, cracking due to drying and shrink swell cycles causes aggregate formation. Biotic factors, on the other hand, are very important in loams and sands (Oades 1993). This was illustrated by Materechera et al. (1992), who observed more small stable aggregates in a heavy clay soil ("black earth soil", 67% clay) than a 19% clay "red-brown earth" soil, though the small aggregates in the clay soil were more stable. Fewer large aggregates and more small aggregates in the heavy clay were caused by wet–dry cycles that led to cracking and shrink–swell activity (Materechera et al. 1992).

A second explanation for limited AS differences may be suboptimal soil C in the arable systems. Novelli et al. (2013) found that cropping intensity (fraction of the year with plant cover) was important in increasing AS in a Mollisol but had no effect in a Vertisol, despite higher SOC stocks and concentration in the Vertisol. They suggested that SOC was important in increasing aggregation in Vertisols only when soils had more than 35 g $C{\cdot}kg^{-1}$ (Novelli et al. 2013). In the 18th year of the Glenlea study, Bell et al. (2012) observed an organic C concentration of 34.4 $g{\cdot}kg^{-1}$ in the grassland compared with 24.3 $g{\cdot}kg^{-1}$ in the organic forage-grain system and 29.7 $g{\cdot}kg^{-1}$ in the grain-only organic system. Only the grassland had an SOC close to the threshold identified by Novelli et al. (2013), which may explain why the grassland had a much higher AS than the arable systems. This requires further research.

Conclusion

Differences in AS between organic and conventional systems were observed in only a few instances after 25 yr of management. Only when the top organic system was compared with the commercial standard conventional system were substantially significant differences observed, but this involved a comparison of different rotation systems (forage-grain in organic vs grain-only in conventional). We also concluded that soil AS was never worse off after 25 yr of organic compared with conventional management. Future studies should compare organic systems, where tillage is a necessity, with no-till conventional systems.

Our second hypothesis that inclusion of a short-term perennial would increase AS in organic production was supported, allowing us to conclude that short-term alfalfa phases in organic rotations are beneficial for soil health even in such a high clay content soil.

Because of declining productivity for the unmanured organic forage-grain system at Glenlea, our third hypothesis stated that adding manure to this P depleted system would boost AS. Surprisingly, this hypothesis was not supported. Manure increased plant growth but did not change AS trends. We therefore conclude that, under the conditions at Glenlea, adding a short-term alfalfa phase to the organic rotation was more important than manure additions for AS improvement, despite the fact that without manure addition, crop productivity declined.

Lastly, our hypothesis that the long-term grasslands would have the highest AS was supported. It is unclear whether the stronger effect of the grassland on AS was due to its perennial grass dominated plant community (with fine roots) or that its C content was above the postulated 35 g C·kg^{-1} level required for AS improvement in Vertisolic soils (Novelli et al. 2013).

This study was conducted using an intensive tillage regime. Future studies should consider low tillage organic production, such as outlined by Halde et al. (2015), in comparison with no-till conventional production.

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References

Acharya, B.S., Rasmussen, J., and Eriksen, J. 2012. Grassland carbon sequestration and emissions following cultivation in a mixed crop rotation. Agric. Ecosyst. Environ. **153**: 33–39.

Angers, D.A. 1992. Changes in soil aggregation and organic carbon under corn and alfalfa. Soil Sci. Soc. America J. **1249**: 1244–1249.

Angers, D.A. and Mehuys, G.R. 1993. Aggregate stability to water. Pages 651–657 in M.R. Carter, ed. Soil sampling and methods of analysis. Lewis Publishers, Boca Raton, FL.

Aoyama, M., Angers, D.A., and N'dayegamiye, A. 1999. Particulate and mineral-associated organic matter in water-stable aggregates as affected by mineral fertilizer and manure applications. Can J. Soil Sci. **79**: 295–302.

Bell, L.W., Sparling, B., Tenuta, M., and Entz, M.H. 2012. Soil profile C and nutrient stocks under long-term conventional and organic crop and alfalfa-crop rotations and re-established grasslands. Agric. Ecosyst. Environ. **158**: 156–163.

Biswas, A.K., Mohanty, M., Hati, K.M., and Misra, A.K. 2009. Distillery effluents effect on soil organic carbon and aggregate stability of a Vertisol in India. Soil Till. Res. **104**: 241–246.

Braman, S., Tenuta, M., and Entz, M.H. 2016. Selected soil biological parameters measured in the 19th year of a long term organic-conventional comparison study in Canada. Agric. Ecosyst. Environ. **233**: 343–351.

Canadian Soil Information Service (CanSIS). n.d. Soils of Manitoba. [Online]. Available from: http://sis.agr.gc.ca/cansis/soils/mb/soils.html [23 Apr. 2019].

Carkner, M., Bamford, K., Martens, J.T., Wilcott, S., Stainsby, A., Stanley, K., et al. 2020. Building capacity from Glenlea, Canada's oldest organic rotation study. Pages 103–122 in Long-term farming systems research. Academic Press.

Entz, M.H., Penner, K.R., Vessey, J.K., Zelmer, C.D., and Thiessen Martens, J.R. 2004. Mycorrhizal colonization of flax under long-term organic and conventional management. Can. J. Plant Sci. **84**: 1097–1099.

Guidi, P., Marè, B.T., and Vianello, G. 2017. Effects of alfalfa on aggregate stability, aggregate preserved-C and nutrients in region mountain agricultural soils 1 year after its planting. Land Degrad. Develop. **2417**: 2408–2417.

Guo, Z., Yan, G., Zhang, R., Li, F., Zeng, Z., and Liu, H. 2010. Improvement of soil physical properties and aggregate-associated C, N, and P after cropland was converted to grassland in semiarid loess plateau. Soil Sci. **175**: 99–104.

Halde, C., Bamford, K.C., and Entz, M.H. 2015. Crop agronomic performance under a six-year continuous organic no-till system and other tilled and conventionally-managed systems in the northern Great Plains of Canada. Agric., Ecosys. Environ. **213**: 121–130.

Hebb, C., Schoderbek, C., Hernandez-Ramirez, D., Hewins, G., Carlyle, C.N., and Bork, E. 2017. Soil physical quality varies among contrasting land uses in Northern Prairie regions, Agric. Ecosyst. Environ. **240**: 14–23.

Helgason, B.L., Walley, F.L., and Germida, J.J. 2010. No-till soil management increases microbial biomass and alters community profiles in soil aggregates. Appl. Soil Ecol. **46**: 390–397.

Hurisso, T.T., Davis, J.G., Brummer, J.E., Stromberger, M.E., Mikha, M.M., Haddix, M.L., et al. 2013. Rapid changes in microbial biomass and aggregate size distribution in response to changes in organic matter management in grass pasture. Geoderma. **193**: 68–75.

Kelling, K.A., and Matocha, J.E. 1990. Plant analysis as an aid in fertilizing forage crops. Pages 429–447 in R.L. Weterman, ed. Soil testing and plant analysis. 3rd ed. Soil Sci. Soc. of America, Madison, WI.

Knight, J.D., Buhler, R., Leeson, J.Y., and Shirtliffe, S. 2010. Classification and fertility status of organically managed fields across Saskatchewan, Canada. Can J. Soil Sci. **90**: 667–678.

Kong, A.Y.Y., and Six, J. 2010. Tracing root vs. residue carbon into soils from conventional and alternative cropping systems. Soil Biol. & Biochem. **74**: 1201–1210.

Kubota, H., Quideau, S.A., Hucl, P.J., and Spaner, D.M. 2015. The effect of weeds on soil arbuscular mycorrhizal fungi and agronomic traits in spring wheat (Triticum aestivum L.) under organic management in Canada. Can. J. Plant Sci. **95**: 615–627.

Larney, F.J., Buckley, K.E., Hao, X., and McCaughey, W.P. 2006. Fresh, stockpiled, and composted beef cattle feedlot manure: Nutrient levels and mass balance estimates in Alberta and Manitoba. J. Environ. Qual. **35**: 1844–1854.

Mäder, P., Fliessbach, A., Dubois, D., Gunst, L., Fried, P., and Niggli, U. 2002. Soil fertility and biodiversity in organic farming. Science **296**: 1694–1697.

Materechera, S.A., Dexter, A.R., and Alston, A.M. 1992. Formation of aggregates by plant roots in homogenised soils. Plant and Soil. **142**: 69–79.

Mueller P., Creamer, N., Barbercheck, M., Raczkowski, C., Bell, M., Brownie, C., et al. 2006. Long-term, large-scale systems research directed toward agricultural sustainability. Pages 79–99 in J. Raupp, C. Pekrun, M. Oltmanns, and U. Kopke, eds. Long-term field experiments in organic farming. International Society of Organic Agriculture Research (ISOFAR), Scientific Series, Berlin, Germany.

Novelli, L.E., Caviglia, O.P., Wilson, M.G., and Sasal, M.C. 2013. Land use intensity and cropping sequence effects on aggregate stability and C storage in a Vertisol and a Mollisol. Geoderma. **195**: 260–267.

Oades, J.M. 1993. The role of biology in the formation, stabilization and degradation of soil structure. Geoderma. **56**: 377–400.

Ozlu, E., and Kumar, S. 2018. Response of soil organic carbon, pH, electrical conductivity, and water stable aggregates to long-term annual manure and inorganic fertilizer. Soil Sci. Soc. Am. J. **82**: 1243.

Pulleman, M., Jongmans, A., Marinissen, J., and Bouma, J. 2003. Effects of organic versus conventional arable farming on soil structure and organic matter dynamics in a marine loam in the Netherlands. Soil Use Manag. **19**: 157–165.

Rillig, M.C., Wright, S.F., and Eviner, V.T. 2002. The role of arbuscular mycorrhizal fungi and glomalin in soil aggregation: comparing effects of five plant species. Plant Soil. **238**: 325–333.

Romano, E.L., Pena-Yewtukhiw, E.M., Waterland, N.L., and Grove, J.H. 2017. Soil health benefit to composted manure application and insertion of a sod component in a long-term organic crop rotation. Soil Sci. **182**: 137–145.

SAS Institute Inc. 2016. Cary, NC, USA.

Siegrist, S., Schaub, D., Pfiffner, L., and Mäder, P. 1998. Does organic agriculture reduce soil erodibility? The results of a long-term field study on loess in Switzerland. Agric. Ecosyst. Environ. **69**: 253–264.

Six, J., Bossuyt, H., Degryze, S., and Denef, K. 2004. A history of research on the link between (micro)aggregates, soil biota, and soil organic matter dynamics. Soil Till. Res. **79**: 7–31.

Sparling, G.P., Graham Shepherd, T., and Kettles, H.A. 1992. Changes in soil organic C, microbial C and aggregate stability under continuous maize and cereal cropping, and after restoration to pasture in soils from the Manawatu region, New Zealand. Soil Till. Res. **24**: 225–241.

Su, Y.Z., Liu, W.J., Yang, R., and Chang, X.X. 2009. Changes in soil aggregate, carbon, and nitrogen storages following the conversion of cropland to alfalfa forage land in the marginal oasis of northwest China. Environ Manage. **43**: 1061–1070.

Thiessen Martens, J.R., Lynch, D.H., and Entz, M.H. 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.

Tisdall, J., and Oades, J.M. 1982. Organic matter and water-stable aggregates in soils. J. Soil Sci. **33**: 141–163.

Vezzani, F.M., Anderson, C., Meenken, E., Gillespie, R., Peterson, M., and Beare, M.H. 2018. The importance of plants to development and maintenance of soil structure, microbial communities and ecosystem functions. Soil Till. Res. **175**: 139–149.

Welsh, C. 2007. Organic Crop Management can decrease labile soil P and promote mycorrhizal association of crops. University of Manitoba. Available from University of Manitoba Libraries MSpace, Winnipeg (MB).

Welsh, C., Tenuta, M., Flaten, D., Thiessen-Martens, J., and Entz, M. 2009. High yielding organic crop management decreases plant-available but not recalcitrant soil phosphorus. Agron. J. **101**: 1027–1035.

Whalen, J.K., and Chang, C. 2002. Macroaggregate characteristics in cultivated soils after 25 annual manure applications. Soil Sci. Soc. Am. J. **66**: 1637–1647.

Williams, D.M., Blanco-Canqui, H., Francis, C.A., and Galusha, T.D. 2017. Organic farming and soil physical properties: An assessment after 40 years. Agron. J. **109**: 600–609.

Wortmann, C.S., and Shapiro, A.C.A. 2008. The effects of manure application on soil aggregation. Nutr. Cyc.l Agroecosyst. **80**: 173–180.

Yoder, R.E. 1936. A direct method of aggregate analysis of soils and a study of the physical nature of erosion losses 1. Agron. J. **28**: 337–351.

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