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

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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 four years 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 were never lower than 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 kg⁻¹ postulated for Vertisols.

Keywords: aggregate stability, organic agriculture, perennials, manure, grassland

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 years. 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-year 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 (eg. 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 ha⁻¹ yr⁻¹ of farm yard manure (FYM), plus 10 t ha⁻¹ yr⁻¹ of slurry during the grass pasture were 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 which 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 kg^{-1} , with values ranging from $0.8\text{--}3.9 \text{ g kg}^{-1}$. About half of all green manures had P concentrations below the critical value of 2.0 g 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 three year organic and conventional rotations, it includes a 15 year 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 five years they found 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 to 120 cm soil profile compared with all arable systems, including those which include short-term perennials (Bell et al. 2012). It was interesting, however, to observe similar levels of 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 compare 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 (ie., 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 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 by 28 metres in size. The organic and conventional plots have been managed as such continuously since 1992, while the current four year 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*), orchardgrass (*Dactylis glomerata*) and red clover (*Trifolium repens*). Forages are seeded in early spring of the first "forage year". Since 2007 composted cattle manure has been added once every four years 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/ha every four years. We estimated total C additions from manure at 3.9 Mg 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 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 (David Lobb, U of M, pers. comm.).

Briefly, crop management consisted of seeding in springtime, fertilization at 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 post-emergence 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 four to five years (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 (May 3-6 and 9-11, 2017). Grassland plots were sampled later (June 9 and 11) 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 4x28 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 cm³).

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 mm, 0.5 mm, 1 mm, 2 mm, 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 were placed on the top sieve which was

under about 0.5cm 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 minute⁻¹ for ten minutes. After sieving, samples were washed into pre-weighed jars, dried at 105° C for 48 hours, and then weighed. Mean weight diameter (MWD), a measure of the size distribution of water-stable aggregates, was calculated using the following formula:

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

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 analysed 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 which 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 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 (ie., 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 (Figure 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 in order to discern the effect of forage within an organic rotation (data in Figure 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 (Figures 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 (Figure 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.

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 (Figure 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 (Figure 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 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. 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 microbial biomass carbon (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* Gaud.) had the greatest effect on AS followed by wheat and then pea (*Pisum sativa*). On the other hand, two to five years 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 one year 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 to inorganic fertilizer (Ozlu and

Kumar 2018, Pulleman et al. 2003). 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 (Figure 4) and forage (Figure 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 (eg., 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 ha^{-1}) the manured treatment produced much more plant biomass (Figures 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 three years after the most recent manure application (ie., manure applied in fall of 1st alfalfa year, but we sampled wheat and flax crops). Wortmann and Shapiro (2007) found that manure increased stable macroaggregates ($>0.25 \text{ mm}$) and decreased microaggregates ($<0.25 \text{ mm}$), but also that its effect on AS was not detectable four years 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 (Figure 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 two-year 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 (4 for the conventional and 3 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 AMF proliferation in wheat managed organically in Alberta. Greater weed abundance and diversity has 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 AMF 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.

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 (Figure 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 to all of the arable treatments.

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 to management factors (eg., 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 was 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 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 kg⁻¹ in the grassland compared with 24.3 g kg⁻¹ in the organic forage-grain system and 29.7 g kg⁻¹ in the grain only organic system. Only the grassland had a 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 years 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 conventional vs grain only in conventional). We also concluded that soil AS was never worse off after 25 years 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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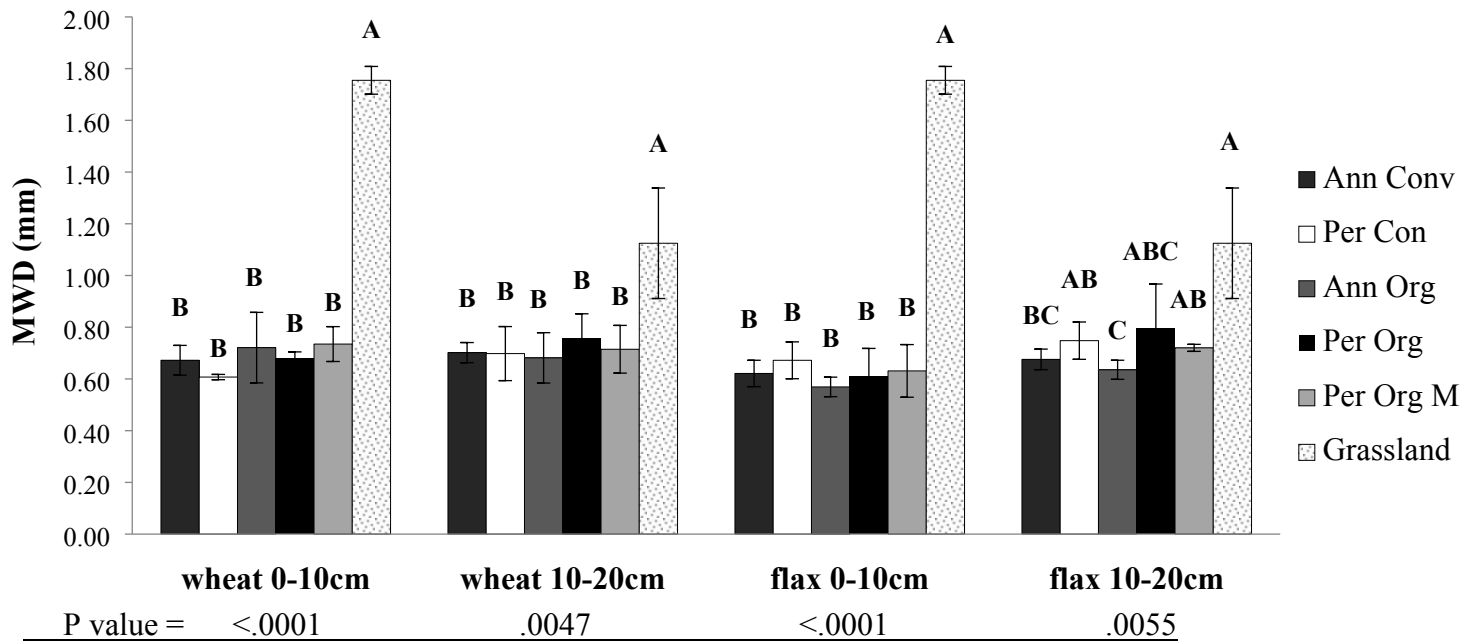


Figure 1. Mean weight diameter (MWD) of stable aggregates in treatments at Glenlea Long-term Rotation in the wheat and flax phases of the rotation at two depths. Ann Conv stands for the annual conventional grain rotation, Per Conv for the conventional forage-grain rotation, Ann Org for the organic annual 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.

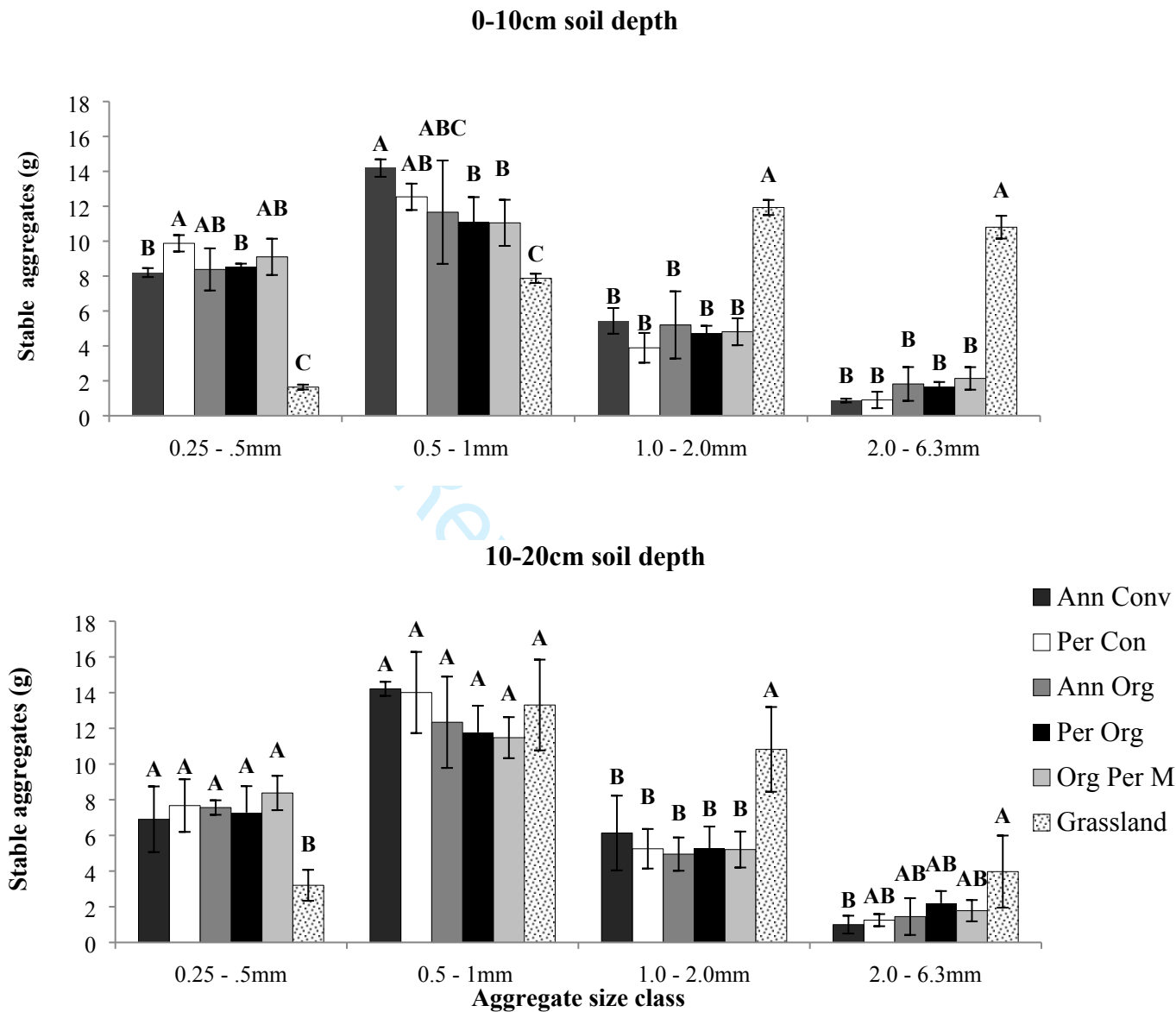


Figure 2. Stable aggregates (g) in individual size classes in treatments at two depths at Glenlea in wheat plots. Ann conv stands for the annual conventional grain rotation, per conv for the conventional forage-grain rotation, ann org for the organic annual grain rotation, per org for the organic forage-grain 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.

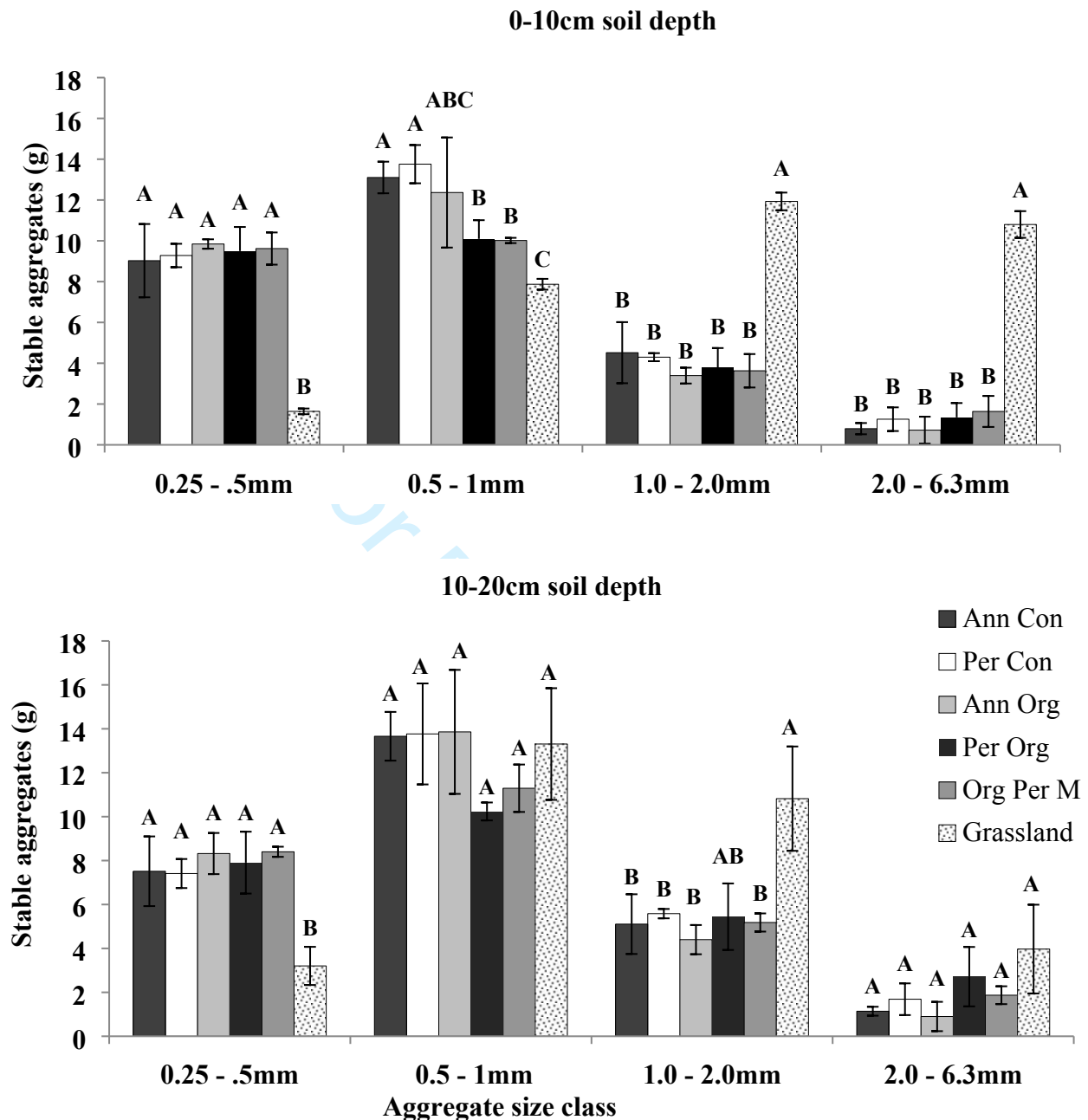


Figure 3. Stable aggregates (g) in individual size classes in treatments at two depths at Glenlea in flax plots. Ann con stands for the annual conventional grain rotation, per con for the conventional forage-grain rotation, ann org for the organic annual grain rotation, per org for the organic forage-grain 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.

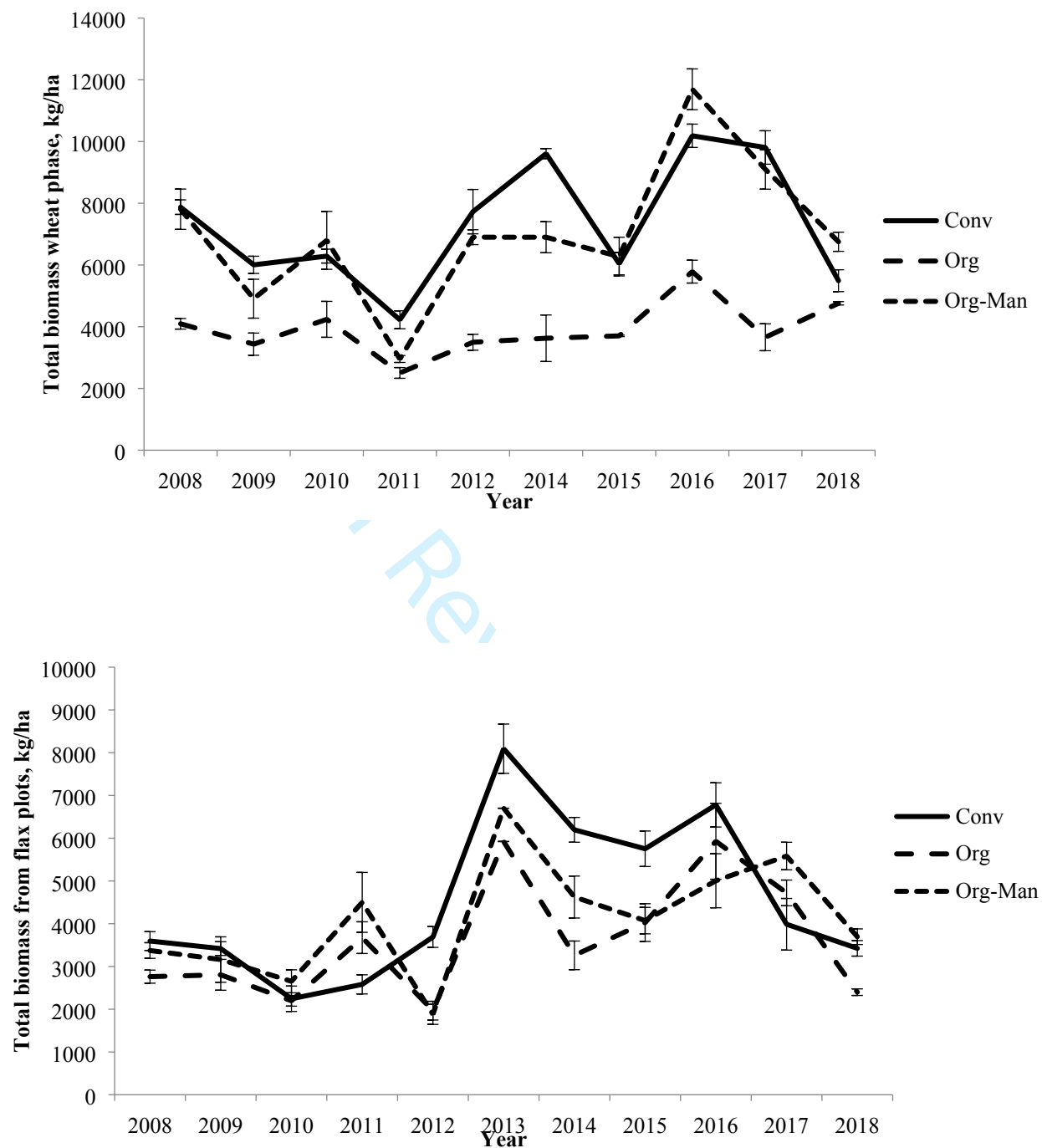


Figure 4. Total aboveground biomass production at time of grain harvest in the wheat (upper) and flax (lower) plots in the forage-grain rotation in conventional, organic (no manure) and organic (with manure) systems.

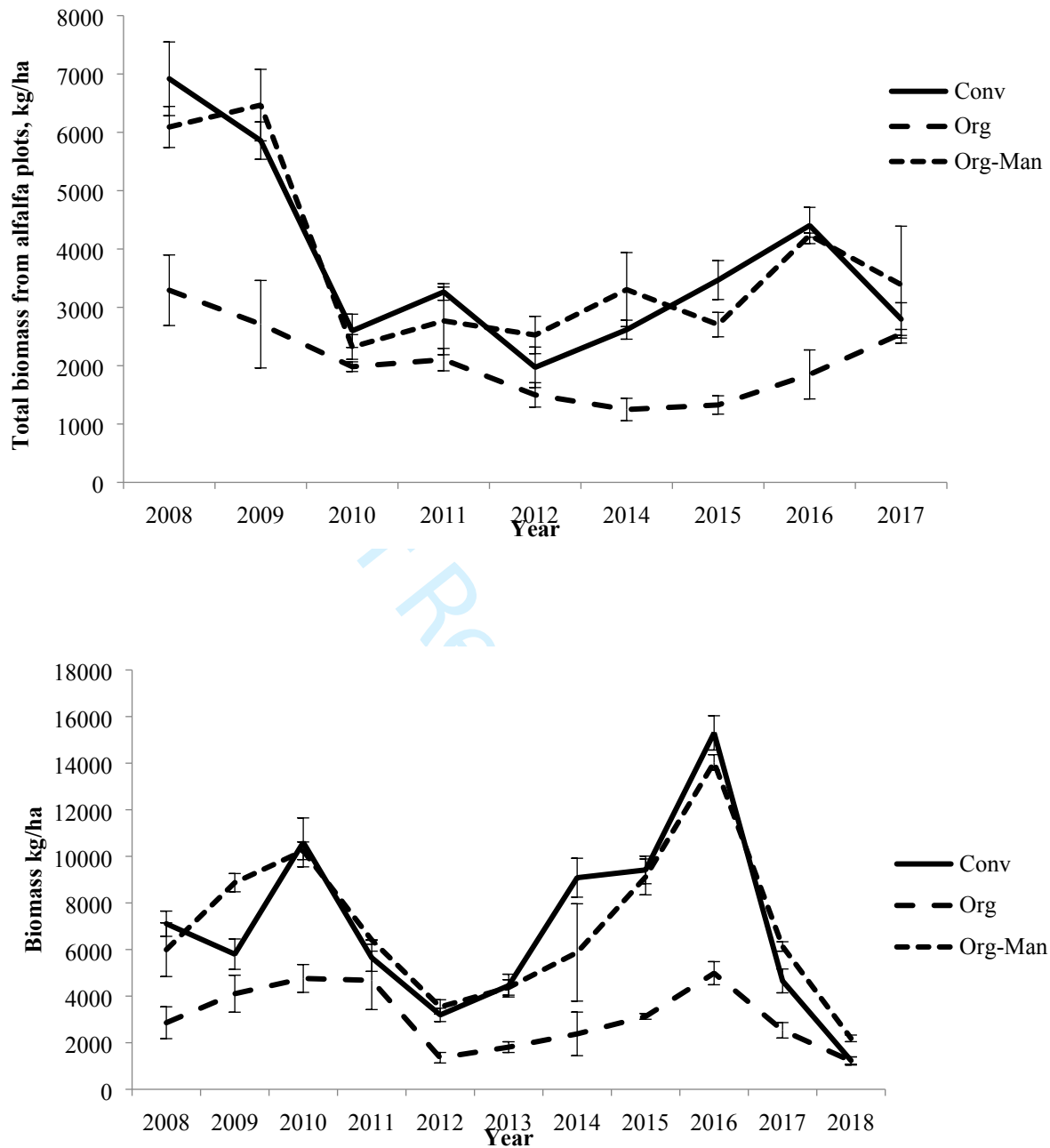


Figure 5. Total aboveground biomass production for alfalfa in the first year of production (upper) and second year of production (lower) in the forage-grain rotation in conventional, organic (no manure) and organic (with manure) systems.

Table 1. Bulk density (g/cm³) in treatments at Glenlea Long-term rotation in the wheat and flax phases of the rotation at two depths. 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.

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

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

	Wheat				Flax			
	0-10cm		10-20cm		0-10cm		10-20cm	
Ann Conv	2.17	C	2.50	B	1.98	B	2.85	B
Per Con	2.26	C	3.13	B	3.14	B	4.22	AB
Ann Org	4.54	BC	3.63	B	1.80	B	2.25	B
Per Org	4.12	BC	5.50	AB	3.38	B	6.78	AB
Org Per M	5.34	B	4.45	AB	4.09	B	4.68	AB
Grassland	27.00	A	9.93	A	27.00	A	9.93	A

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