Effects of reduced tillage in organic farming on yield, weeds and soil carbon: Meta-analysis results from the TILMAN-ORG project

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Abstract

Within the CORE ORGANIC II project, TILMAN-ORG, we have compiled data from ongoing trials and the published literature to conduct a meta-analysis on the effects of reduced tillage on yields, weed pressure and soil C in organic farming. The results indicate that replacing deep inversion tillage with some form of reduced tillage intensity results in yield declines of 5-10%; however, relative to shallow inversion tillage, there is no yield penalty from further reducing tillage intensity. Weed pressure does not appear to be the sole cause of yield declines. Reducing tillage intensity also offers an opportunity to further increase the soil C sequestration ecosystem service provisioning of organic farming. Humid oceanic climates are least suited to implementation of reduced tillage systems in organic farming, while the production in the Mediterranean appears to benefit from reduced tillage. The study has highlighted the need for flexible, region- and system-specific design of reduced tillage systems in organic farming.

Introduction

The TILMAN-ORG project brought together 15 partner organizations in 11 European countries to address the challenge of compiling and translating knowledge on conservation agriculture in organic farming systems. While conservation agriculture (CA; the use of reduced tillage practices in combination with increased vegetative soil cover) is increasingly adopted in conventional farming systems, uptake by the organic sector has lagged behind. This is due to the real or perceived challenges of implementing CA in organic systems where interventions such as herbicides and N fertilizer are not permitted.

A major activity within TILMAN-ORG was the compilation of unpublished data from existing field trials where CA was tested under organic conditions. In addition, the peer and non-peer reviewed literature was also compiled. The objective of this activity was to create a database of trial results and use this data to conduct a statistical meta-analysis that would address the questions:

1. What is the magnitude of the effect of reduced tillage intensity on crop yields in organic systems?
2. Is this effect consistent across all environments (soil types and climatic zones)?
3. Are there certain management practices that can be used to enhance production under reduced tillage in organic systems i.e. crop rotation, crop choice (current and previous year), use of mechanical weeding?
4. Does the potential negative yield effect using CA in organic systems reduce over time?
5. Is it really weed pressure that is causing yield reductions? Or could there be other factors?
6. Does using reduced tillage in organic systems increase soil organic C above the levels already achieved by organic practice?

Material and methods

Data from a total of 14 field trials were compiled. This included trials located in 8 European countries and Canada. A literature survey of non-peer and peer-reviewed published literature was conducted to identify articles that reported results from experiments using reduced tillage in organic farming systems using the ISI-Web of Science and CAB Abstracts (Ovid) from 1910 to 2013. This provided around 180 articles published from 1986 to 2013 in scientific journals from the Journal Citation Report. More relevant papers were found by searching through the reference lists of papers already selected for the meta-analysis and recommendations of experts in tillage research. Papers were scrutinized and included if they met the following selection criteria: i) experiment under organic management for at least three years prior to the date of response measurement;

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ii) at least two levels of tillage intensity included as a treatment; iii) no "mixing" of treatments i.e. only tillage varied between experimental treatments; iv) included climatic zones found in Europe.

For both data sources (published and field trials) values for response variables were provided as means for each treatment and information on the number of replications (N) and variability of the mean (standard error or standard deviation) were recorded. In each experiment the tillage treatment factor was assigned to a class based on the level of tillage intensity. The six classes in order of decreasing intensity were: deep inversion tillage (>25 cm depth), double-layer ploughing, shallow inversion tillage (<25 cm depth), non-inversion tillage (10-25 cm depth), non-inversion tillage (<10 cm depth), and no-tillage. Environmental variables included as factors were soil type and climate as described in Quemada et al. (2013) while management factors were crop rotation class, mechanical weeding class and main crop and previous crop. All data was summarized in a database to allow easy manipulation and extraction of key subsets.

For crop yields and weed data the effect size was calculated as the ratio between the experimental and control treatments. This resulted in an effect size that was standardized and unitless; therefore it was not necessary to have the same units of measurement when combining data from different experiments. For the soil C data, since all measurements were in the same units (g m-2) the effect size was calculated as the mean difference. This allowed presentation of the effect in actual units of mass per area.

Data were analysed using meta-analysis techniques to study the effects of reduced tillage on crop yield, soil C and weed pressure. All data were analyzed using the R statistical software package (www.r-project.org) (R Development Core Team 2011). An observation pair consisted of a datapoint for a designated control treatment and a datapoint for an experimental treatment. The effect size for each yield and weed pressure observation pair was calculated as the response ratio (r = Xe/Xc), where Xe is the experimental treatment mean and Xc is the control mean of each variable. For the soil C data, since all measurements were in the same units (g m-2) the effect size was calculated as the mean difference (MD=Xe-Xc). Mean effect sizes were calculated for each variable of interest and data-set category, and bias-corrected 95% confidence intervals (CI) were generated by a bootstrapping procedure (5000 iterations). Means were considered significantly different from zero if the 95% CI did not overlap zero, and different from one another if their 95% CIs interval were non-overlapping (Hedges et al. 1999). The results of each mean ratio (r) were expressed as % effect size (e), where e = (r-1)×100. The data was divided into two subsets: subset one consisted of observation pairs where deep inversion tillage was included as the "control" treatment, and subset two consisted of observation pairs where shallow inversion tillage was the "control" treatment.

Results

A total of 901 observation pairs were identified for the comparison "reduced tillage" versus "deep inversion tillage" under organic management in subset one. Reducing tillage resulted in an average yield decline of 5-10% relative to the deep inversion control. For the subset of data where the control was shallow inversion tillage (178 observation pairs) there was no significant reduction in crop yield by reducing tillage under organic management, and there was actually a significant increase in yield for the 26 observation pairs where no-tillage was used compared with shallow inversion tillage.

Yield reductions due to reducing tillage intensity in organic systems were significant for all climate classes except for the Mediterranean group within the subset with shallow inversion as a control. For this set, yields were increased relative to the control by nearly 10%. There were no clear trends for the impact of soil type on these effects.

Yields of legume leys and cover crops were the least affected by reductions in tillage intensity, while other crop types appeared to be equally affected by reduced tillage. The crop rotation system also did not result in a differentiation of the yield effect when tillage intensity was reduced.

For both subsets of data weed pressure was significantly higher when tillage intensity was reduced. However, weed pressure only correlated with reduced yield when double-layer ploughing or shallow inversion tillage were implemented instead of deep inversion tillage was the control; when compared to shallow inversion tillage, the reduction in crop yields correlated with increased weed pressure when deep non-inversion tillage was used.

As expected, reducing tillage intensity increased soil C stocks compared with deep inversion tillage (183 observation pairs); however, soil C stocks were only higher when no-tillage was used when compared to shallow inversion tillage (74 observation pairs).

Discussion

This analysis confirmed that using reduced tillage in organic farming systems can result in yield reductions; however, it also demonstrated that this was only the case when tillage intensity was reduced relative to deep inversion tillage. Yield reductions were not always correlated with increased weed pressure, which suggests that other factors may also be inhibiting yields when reduced tillage is used in organic systems. These may include reduced rates of N mineralization from soil organic N sources in the early spring due to colder surface soil temperatures, as suggested by Mäder et al. (2012). A more in depth analysis of this database will further elucidate the mechanisms of yield reduction when reduced tillage is used in organic farming systems. This analysis will also help to identify optimum management practices (crop rotations, crop choice, tillage intensity) needed to realize the ecosystem services of conservation agriculture, while also maintaining crop yields.

Suggestions to tackle the future challenges of reducing tillage in organic farming systems

A key recommendation is that "hybrid" systems will need to be adopted in organic farming, so that farmers can use deep inversion tillage at key stages of the rotation when weed control and/or incorporation of a green manure is required, or for removal of grass-clover leys. Special attention however has to be paid to the fact that one single deep inversion ploughing may lead to an immediate loss of accumulated soil organic carbon and that large pores built by earthworms and roots may be disrupted. Carbon models may further be adopted using datasets from reduced tillage systems under organic management to predict soil organic carbon with more accuracy in the long-term, and CA techniques may be improved in on-farm experiments in a participatory way with farmers. It is also useful to note that special equipment, e.g. the double-layer plough for primary tillage, does not appear to offer a benefit over simple shallow inversion tillage with a mouldboard plough. The potential to use conventional equipment when reducing tillage intensity should make this option more attractive to the organic farming community. However special equipment like chisels with large goose feet sweeps or a stubble cleaner to undercut the soil and thereby control weeds, and special ploughs to superficially till the soils may still be useful.

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