Weed–crop competition relationships differ between organic and conventional cropping systems

M R RYAN*, R G SMITH*, D A MORTENSEN*, J R TEASDALE†, W S CURRAN*, R SEIDEL‡ & D L SHUMWAY§

*Department of Crop and Soil Science, The Pennsylvania State University, University Park, PA, USA, †USDA-ARS Sustainable Agricultural Systems Laboratory, Beltsville, MD, USA, ‡The Rodale Institute, Kutztown, PA, USA, and §Department of Statistics, The Pennsylvania State University, University Park, PA, USA

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Summary
Experiments comparing conventional and organic systems often report similar yields despite substantially higher weed abundance in the organic systems. A potential explanation for this observation is that weed–crop competition relationships differ between the two types of systems. We analysed weed and crop yield data from the Rodale Institute Farming Systems Trial (FST), which provides a unique 27-year dataset of a conventional (CNV) and two organic [manure (MNR) and legume (LEG)] soyabean (Glycine max (L.) Merr.) and maize (Zea mays L.) cropping systems. Average soyabean yields were similar between the MNR and CNV systems and only slightly reduced in the LEG system, whereas average maize yields did not differ among systems despite the two organic systems having more than four and six times greater weed biomass in soyabean and maize respectively. Plot-level weed biomass–crop yield relationships indicated that weed–crop competition differed between the two organic and CNV systems in maize, and was strongest in the CNV system, intermediate in the LEG system and weakest in the MNR system. These results suggest that organic cropping systems may be able to tolerate a greater abundance of weeds compared to conventional systems and that fertility management within organic systems may influence weed–crop competition.

Keywords: weeds, competition, organic, conventional, long-term, cropping systems, maize, soyabean, crop yield, legume, manure.


Introduction
The effect of weeds on crop yield has been widely studied and models describing the relationship between weed abundance and crop yield have been useful for predicting yield loss and assisting with developing management guidelines (Zimdahl, 2004). Previous research has highlighted the use of early-season weed density to estimate yield loss, so the cost of increased management could be weighed against the potential yield reduction (Coble & Mortensen, 1992). More advanced simulation models based on weed–crop competition relationships were developed and have further assisted management and research (Bastiaans et al., 1997; Van Ittersum et al., 2003; Nesser et al., 2004). Weed abundance and crop performance models have also been useful for characterising the effects of weeds on crop yields under different management systems; this approach allows researchers to evaluate the effectiveness of suites of tactics applied together (Bastiaans et al., 2008).

One area of research where weed–crop competition modelling can be particularly insightful is in assessing potential differences in the competitive effects of weeds in organic and conventional cropping systems. An
accumulating body of literature (Davis et al., 2005; Delate & Cambardella, 2004; Hiltbrunner et al., 2008; Posner et al., 2008) suggests that despite the presence of relatively high levels of weeds, crops grown in systems with more complex crop rotations and cultural practices can produce yields that are comparable with conventionally grown crops with relatively low levels of weeds. Davis et al. (2005) found that organic and conventionally grown soyabean (Glycine max (L.) Merr.) produced similar yields, despite four times as much weed biomass in organic systems in Michigan, USA. Delate and Cambardella (2004) reported equal or higher organic maize (Zea mays L.) and soyabean yields in Iowa, USA, despite higher weed biomass levels. Hiltbrunner et al. (2008) reported wheat and maize yields in Switzerland were equivalent under organic and conventional management in spite of seven and 15 times the weed abundance in organically managed wheat and maize, respectively. While it is unlikely that any one factor could account for the surprisingly high crop tolerance to weeds reported in these studies, it is likely that the organically managed soils, with associated organic matter inputs and nutrient pools, are an important factor (Bauer & Black, 1994; Liebman & Davis, 2000).

Given the increasing number of studies on soyabean and maize (where soil fertility is not a limiting factor) reporting similar or only slightly decreased yields in organic systems despite high weed abundance, we set out to evaluate the relationship between weed biomass and crop yield in greater detail than had been done in previous reports. We examined 27 years of data from a cropping systems experiment that, to our knowledge, is the longest running comparison of organic and conventional maize and soyabean production in North America. Previous reports from that experiment (Peters, 1991; Liebhardt et al., 1989) have shown that organic maize yields were lower than yields in the conventional (CNV) system during the first four years of the experiment, but were equivalent when averaged over the first 21 years of the experiment (Pimentel et al., 2005). Although crop yield data have been reported, there has not been an explicit evaluation of the relationship between weed abundance and yield of maize and soyabean. Thus, this data set provides a unique opportunity to test whether organic management influences this relationship. Our hypotheses are: (i) the relationship between crop yield and weed biomass differs between cropping systems and (ii) yield loss per unit weed biomass is greater in the CNV compared with the organic cropping systems. Because of the long-term nature of the data set, the relationships observed in this experiment encompass a wide range of crop yields, weed biomass levels and growing-season weather conditions. This allows for a more comprehensive assessment of weed–crop relationships than have been afforded in the past through analysis of 2–3 years experiments. Furthermore, because this is a systems study, the cropping system treatments incorporate multiple management tactics that differ between the systems, thus increasing the relevance of the results to farmers.

Materials and methods

Study site and experimental design

Data used to analyse the relationship between weed biomass and the yield of maize and soyabean that were managed using organic and conventional methods were collected in the Rodale Institute Farming Systems Trial (FST). The ongoing FST was initiated in 1981 at the Rodale Institute in Berks County, south-eastern Pennsylvania (40°37′97″N and 75°56′98″W). The 6.1 ha field site is nested in a 135 ha research farm that has been managed organically since 1975. The soil is a moderately well drained Comly silt loam with small areas of Berks shaley silt loam and Duffield silt loam. Prior to the initiation of the FST, the field site was farmed conventionally in a maize–wheat rotation (Liebhardt et al., 1989). The experimental design is a split-plot randomised complete block with eight replications. Main plots consisted of one CNV and two organic systems. Main plots measured 18 × 92 m and were separated by 1.5 m grass strips to minimise transport of soil, fertilisers and pesticides among cropping system plots. Within each main plot, there were three subplot treatments (crop rotation sequence entry points) which were 6 × 92 m. Entry point subplots ensured that multiple crops from the rotations were present each year. Mean annual growing degree-day accumulation is 1554 (base 10°C) and mean annual rainfall is 1150 mm (Lotter et al., 2003). Additional field site and experiment details can be found in Liebhardt et al. (1989), Lotter et al. (2003) and Pimentel et al. (2005).

Cropping systems

A summary of management practices conducted in the main plots is found in Table 1. The two organic systems differed primarily in fertility source and were either manure (MNR) or legume (LEG) based. In the MNR system, cattle manure was applied at 18 Mt ha⁻¹ (wet weight) for grain maize and 27 Mt ha⁻¹ (wet weight) for silage maize. In the LEG system red clover (Trifolium pratense L.) or hairy vetch (Vicia villosa Roth) were planted as cover crops before maize and served as the primary N source. In 1991, 1996 and 2005, hairy vetch in the LEG system was winter-killed and in 2005 a supplemental application of organic
fertiliser 5-3-4, containing colloidal phosphate, langbeinite, porcine blood meal, steamed bone meal, plant protein product and compost was applied at 430 kg ha\(^{-1}\) in this system.

In contrast to the two organic systems, mineral fertiliser was the fertility source in the CNV system. Although specific formulation and application rates varied somewhat over the 27-year period, in general, a split application made with 34 kg ha\(^{-1}\) of N, 34 kg ha\(^{-1}\) of phosphorus (P\(_2\)O\(_5\)) and 11 kg ha\(^{-1}\) of potassium (K\(_2\)O) was applied as a starter fertiliser at planting and an 114 kg ha\(^{-1}\) of N dribble applied between maize rows c. 45 days after planting. The fertiliser was applied as urea ammonium nitrate or monoammonium phosphate. In all three systems, potassium was applied as needed, based on soil test recommendations, with potassium sulphate (K\(_2\)SO\(_4\)) applied in the MNR and LEG systems and potassium chloride (KCl) applied in the CNV system. Calcitic lime was applied across all systems based on soil test recommendations.

Because the FST was established as a systems experiment, some management practices were unique to each of the main plot treatments and represented best management practices. For instance, crop planting date was determined based on a number of criteria, including rainfall, soil temperature and cover crop maturity and thus varied among the systems. Typical planting dates for conventionally grown maize and soyabean were May 15 and 30 respectively. In the two organic systems, maize and soyabean were planted c. 2 weeks after they were planted in the CNV system. Delayed planting in the organic systems relative to the CNV is a typical cultural pest management strategy in the mid-Atlantic region of the USA. Soyabees were planted in 76 cm rows in the MNR and LEG systems to allow for cultivation and were planted with a grain drill in 19 cm rows in the CNV system. Maize was planted in 76 cm rows in all systems and standard seed treatments were used in the CNV systems. Soil in the MNR and LEG system was typically mouldboard ploughed to a depth of 19 cm prior to crop establishment, whereas soil in the CNV system was chisel ploughed to a depth of 23 cm. Soil was then disked and firmd with a cultimulcher prior to planting.

These practices eliminated weed seedlings in seedbeds at the time of maize and soyabean planting.

Weed management practices differed between the organic and CNV systems. Cultural and mechanical practices were used in the MNR and LEG systems and included delayed planting, cover crops and rotation involving summer grown row crops and overwintering cereals. Mechanical weed management was implemented based on weed density and ability to cultivate, as determined by soil moisture and crop height. Mechanical weed management in maize and soyabean consisted of one to two passes with a rotary hoe or spring tine cultivator prior to crop emergence, one to two passes with a rotary hoe or spring tine cultivator after crop emergence and one to three passes with an inter-row cultivator depending on weed density and environmental conditions.

Chemical weed management was used in the CNV system. Herbicide programmes for the CNV system were developed with guidance from county-based extension educators and from The Pennsylvania State University Agronomy Guide (Curran et al., 1981–2007). Although there have been slight deviations in specific practices over the 27 years of the experiment, typical weed management in soyabean in the CNV system included chloracetamide (e.g. metolachlor), dinitroanaline (e.g. pendimethalin), sulphonylurea (e.g. chlorimuron) and triazine (e.g. metribuzin) herbicides. Typical weed management in maize in the CNV system included pre-emergence applications of chloracetamide (e.g. metolachlor), dinitroanaline (e.g. pendimethalin) and triazine (e.g. atrazine) herbicides.

**Cropping system rotations**

Each of the three management system treatments in the FST involved different rotations of maize and soyabean. The rotations in the MNR and LEG systems were a 5-year sequence of maize–soyabean–silage maize–wheat–hay and a 3-year sequence of maize–soyabean–wheat respectively. The rotation in the CNV system was a 5-year sequence of maize–soyabean–maize–maize–soyabean. Subplot treatments at the FST were crop

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**Table 1** Summary of management differences across cropping systems: manure (MNR); legume (LEG) and conventional (CNV) in the Farming Systems Trial

<table>
<thead>
<tr>
<th>Practice</th>
<th>MNR</th>
<th>LEG</th>
<th>CNV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nitrogen source</td>
<td>Manure</td>
<td>Cover crops</td>
<td>Mineral</td>
</tr>
<tr>
<td>Winter cover crop</td>
<td>Rye</td>
<td>Rye, hairy vetch</td>
<td>None</td>
</tr>
<tr>
<td>Primary tillage</td>
<td>Mouldboard</td>
<td>Mouldboard</td>
<td>Chisel</td>
</tr>
<tr>
<td>Planting date</td>
<td>Late</td>
<td>Late</td>
<td>Early</td>
</tr>
<tr>
<td>Herbicide application(^*)</td>
<td>None</td>
<td>None</td>
<td>1–2</td>
</tr>
<tr>
<td>Rotary hoe cultivation</td>
<td>1–2</td>
<td>1–2</td>
<td>None</td>
</tr>
<tr>
<td>Inter-row S-tine cultivation</td>
<td>1–2</td>
<td>1–2</td>
<td>None</td>
</tr>
<tr>
<td>Inter-row hoe cultivation</td>
<td>1–2</td>
<td>1–2</td>
<td>None</td>
</tr>
</tbody>
</table>

\(^*\)Number of applications made in one growing-season.
rotation entry points that provided the opportunity to grow three of the crops within each cropping system rotation each year. Over the 27-year period, there were several minor changes to the crop and rotation sequences within the three management system treatments. In the LEG system, red clover or hairy vetch were frost seeded into or sown after wheat. Cereal rye (Secale cereale L.) was planted after maize in both organic systems since 1992. In 2003, all crop rotation entry points were planted to oats to prepare for a transition to a standard rotation of maize–soyabean–wheat across all systems.

**Crop yield and weed biomass sampling**

Maize and soyabean grain yields were measured with a plot combine that harvested a 3 by 92 m swath in each subplot. Grain samples were collected at harvest to determine moisture content. All grain yields are reported at 0% moisture. Above-ground weed biomass was determined annually in maize and soyabean in all three management systems by clipping and removing all non-crop plant species in at least two randomly placed 0.5 m² quadrats from all replicates in mid- to late-August (peak weed biomass). Samples were dried to less than 5% moisture and weighed.

Due to the lack of weed community data over the length of the experiment, our analysis is focused explicitly on describing the relationship between total weed biomass and crop yield. In this analysis, we summarised the competitive effect of the entire weed community by determining the relative yield loss per unit weed biomass. Previous studies conducted in this long-term experiment have provided descriptions of the weed communities in the three cropping systems at various times. Liebhardt et al. (1989) reported data on weed community composition in maize during the first several years of the experiment. Maize was dominated by *Setaria* spp. until the 5th year of the experiment, after which the community became increasingly dominated by annual broadleaf weeds including *Chenopodium album* L., *Abutilon theophrasti* Medik. and *Amaranthus* spp. (Liebhardt et al., 1989). Peters (1991) reported that dominant species in the organic systems included *Setaria* spp., *Amaranthus* spp., *C. album* and *Calystegia sepium* (L.) R. Br., while other weeds such as *Cirsium arvense* (L.) Scop., *Rumex* spp., *Elytrigia repens* (L.) Nevski, *Plantago* spp., *Ambrosia artemisiifolia* L., *Galinusga ciliata* (Raf.) Blake and *A. theophrasti* were present at lower densities. Weed communities were also assed in 2005 and 2006 and showed that the organic systems were dominated by annual species, including *Setaria faberi* Herrm., *A. theophrasti*, *A. artemisiifolia*, *C. album* and *Polygonum pensylvanicum* L. Perennial species including *C. arvense*, *Taraxacum officinale* F.H. Wigg., *Aster pilosus* Willd., were common along with annuals such as *S. faberi*, *A. artemisiifolia* and *Bidens frondosa* L. in the CNV system (Ryan, 2007). Consistency in weed community composition across the three sampling events suggests that weed communities diverged rapidly because of the differential selection pressures (herbicides vs. tillage) in the three management systems, but that the communities stabilised relatively quickly after the study was initiated.

**Data analysis**

**Crop yield and weed abundance**

Weed biomass and maize and soyabean yield data were subjected to ANOVA and mean separation with the Tukey-Kramer method (*P* < 0.05) using Proc Mixed in SAS version 9.1 (SAS Institute, Cary, NC, USA; SAS, 2007). Plot-level data were pooled across entry point subplots and years within each block (*n* = 8) to avoid temporal pseudoreplication. Therefore, these data were analysed as a randomised complete block design instead of a split-plot design. Analyses were performed with cropping system as a fixed effect and block and the cropping system by block interaction as random effects. This model allowed us to describe the data that were used to assess weed–crop competition relationships over the entire range of climatic and environmental conditions encompassed in the experiment.

To graphically represent the response of crop yields and weed biomass to the three cropping system treatments, box plots were used to show the distribution of plot-level weed biomass and crop yield data. Boxes represent the middle 50% (interquartile range, IQR) of the data and the line indicates the median. Bars extend down to the minimum value unless the distance to the minimum value is more than 1.5 times the IQR below the first quartile. In that case, the bar extends to 1.5 times in the IQR from the first quartile. A similar rule applies to the upper bar extending above the third quartile. The notches in the boxes provide an estimate of the 95% confidence interval of the median and can be used to assess differences between two medians (Chambers et al., 1983). Box plots were constructed using R version 2.4.0 (R Foundation for Statistical Computing, Vienna, Austria; R Development Core Team, 2007).

**Modelling weed–crop competition**

The influence of weed abundance on crop yield was quantified using the rectangular hyperbola model. In this model, the yield reducing effect of a weed is expressed as the parameter *i₂*, which describes the initial slope of the hyperbolic function and thus the fractional yield loss per unit weed biomass (*Nw*; g m⁻²) as *Nw*...
approaches zero (Spitters, 1983). A simplified version of this model was used to test the additive effects of weed biomass at a single crop density, which is an efficient and acceptable alternative to replacement series data where crop density is deliberately varied (L. Bastiaans, pers. comm.). Unlike other common hyperbolic yield-loss models that use per cent control as the response variable, this model uses actual yield. This allowed us to assess yield production potential of the different cropping systems. The modified rectangular hyperbola model for the additive design is expressed as:

$$Y_c = \frac{a_0 N_c}{1 + i_w N_w}$$  \hspace{1cm} (1)

where \(Y_c\) is crop yield (g m\(^{-2}\)), \(a_0\) is the reciprocal of the weed-free individual crop plant weight (plant g\(^{-1}\)) and \(i_w\) is the fraction yield loss per unit weed biomass as weed biomass approaches zero (m\(^2\) g\(^{-1}\)). When crop yield is plotted as a function of weed biomass, the maximum possible yield (y-intercept) is determined by \(a_0\) parameter and the slope of the relationship is determined by the \(i_w\) parameter (Fig. 1).

Because we were interested in evaluating weed–crop competition relationships across the entire range of environmental conditions experienced during the course of the study, all available plot-level data were used in the regression analysis. Curve fitting was performed using the nls function (nonlinear least squares) in the open source software R version 2.4.0. We then used an \(F\)-test (Zar, 1999) to determine if there were significant overall effects of management system on the relationship between crop yield and weed biomass, using:

$$F = \frac{(\text{SSE}_{\text{Combined}} - \text{SSE}_{\text{Separate}})/(\text{df}_{\text{Combined}} - \text{df}_{\text{Separate}})}{\text{SSE}_{\text{Separate}}/\text{df}_{\text{Separate}}}$$  \hspace{1cm} (2)

where \(\text{SSE}_{\text{Combined}}\) is the sum of squares from the model when treatment data were pooled as one data set; \(\text{SSE}_{\text{Separate}}\) is the sum of squares from the model when treatments are analysed individually; \(\text{df}_{\text{Combined}}\) is the degrees of freedom for the model when compared treatments are analysed as one data set and \(\text{df}_{\text{Separate}}\) is the sum of degrees of freedom for the model when compared treatments are analysed individually. The \(F\) statistic was then compared to an \(F\) distribution to determine significance. This test provides a metric to compare the fit of the model across all weed biomass levels, rather than at the extreme high and low values (Lindquist et al., 1996).

### Results

#### Crop yields and weed biomass

Across all three systems, annual soyabean yields at the plot-level ranged from 22 to 328 g m\(^{-2}\) (mean = 248 g m\(^{-2}\)) and weed biomass ranged from 0 to 980 g m\(^{-2}\) (mean = 79 g m\(^{-2}\)). When averaged across the 27-year experiment, mean weed biomass in soyabean was more than four times greater in the organic systems (136 and 108 g m\(^{-2}\) in MNR and LEG, respectively) compared with the CNV system (24 g m\(^{-2}\)). Despite this difference in weed biomass, there was no difference between the mean soyabean yields in the MNR compared with the other systems. Mean soyabean yield was 245, 237 and 258 g m\(^{-2}\) in the MNR, LEG and CNV cropping systems, respectively, and was higher in the CNV compared with the LEG system. Comparison of the box plots of soyabean yields and associated weed biomass data showed greater similarity in the distribution of yield data between the three systems than that for weed biomass, which had a smaller range in the CNV compared with the organic systems (Fig. 2).

In maize, yield ranged from 1 to 1167 g m\(^{-2}\) (mean = 624 g m\(^{-2}\)) and weed biomass ranged from 0 to 1043 g m\(^{-2}\) (mean = 81 g m\(^{-2}\)). Mean weed biomass in maize was more than six times greater in the organic systems (138 and 139 g m\(^{-2}\) in the MNR and LEG systems) compared with the CNV system (136 g m\(^{-2}\)).

![Fig. 1 Diagram of the effects of varying parameters in the modified rectangular hyperbola model (Eqn 1).](image-url)
systems, respectively) compared with the CNV system (22 g m\(^{-2}\)). Despite greater weed biomass in the organic systems, there was no difference between the three systems in maize yield (\(P > 0.1\)), which averaged 608, 607 and 642 g m\(^{-2}\) in the MNR, LEG and CNV cropping systems respectively. Comparison of the box plots of maize yield and associated weed biomass data indicated a greater range in crop yield data between the three systems than in weed biomass data, which had a smaller range in the CNV compared with the two organic systems (Fig. 3).

**Weed–crop competition**

Relationships between weed biomass and yield in soya-bean were significant in all three management systems, indicating that increasing weed abundance was associated with decreasing crop yields (Table 2). Weed–crop competition relationships among the three cropping systems were not significantly different (\(P > 0.05\)); however, the relationships between soya-bean yield and weed biomass (Fig. 4) suggested that weed–crop competition was weakest in the MNR, intermediate in the LEG and strongest in the CNV system.

In contrast to soya-bean, the relationships between weed biomass and maize yield differed between management systems (Fig. 5). There was no relationship between weed biomass and maize yield in the MNR system (\(P = 0.12\)) indicating that increasing weed abundance was not associated with decreasing maize yield in this system. This lack of significance is particularly striking, given weed biomass in the MNR system ranged from near zero to in excess of 5000 kg ha\(^{-1}\). In the LEG and CNV systems, the relationship was significant (LEG: \(P < 0.001\); CNV: \(P < 0.0001\)); however, the nature of the relationship differed between the two systems and was significantly more negative in the CNV system (CNV vs. LEG: \(P = 0.0012\)), indicating that increasing weed abundance was associated with a greater reduction in yield in the CNV compared with the LEG system (Table 2). Similar to the soya-bean data, the relationship between maize yield and weed biomass (Fig. 5) indicated that weed–crop competition was weakest in the MNR, intermediate in the LEG and strongest in the CNV system.
Discussion

Weed–crop competition relationships were characterised for two organic and one CNV cropping system using 27 years of data spanning a wide range of growing conditions. Mean weed biomass was 4.5–6.3 times greater in the organic systems compared with the CNV. Despite higher weed biomass in the organic systems, there was no difference in maize yields between the organic and CNV systems. Soyabean yields did not differ between the MNR organic system and the CNV system. However, soyabean yield in the LEG organic system was 8% lower (P < 0.05) than the CNV. These results are congruent with previous research showing that crop yields are often similar or only slightly reduced (P > 0.05) in organic compared with CNV cropping systems (Davis et al., 2005; Delate & Cambardella, 2004; Hiltbrunner et al., 2008; Posner et al., 2008). In this experiment, the fact that the organic systems produced yields that were comparable to the CNV system despite differences in weed biomass between the three systems supports the hypothesis that weed–crop competition relationships differ between cropping systems.

To assess the validity of our second hypothesis, that yield loss per unit weed biomass is greater in the CNV compared with the organic cropping systems, we used nonlinear regression to fit a modified rectangular hyperbola model to the 27-year data set to quantify the relationship between crop yields and weed biomass in each cropping system. In maize, the relationships between yield and weed biomass in the two organic systems were different from the CNV system.

Table 2 Weed competition coefficients from the modified rectangular hyperbola model (Eqn 1) characterising weed–crop competition relationships between crop yields and weed biomass across cropping systems

<table>
<thead>
<tr>
<th>Crop</th>
<th>System</th>
<th>$a_0$ (plant g$^{-1}$)</th>
<th>$i_w$ (m$^{-2}$ g$^{-1}$)</th>
<th>$R^2$</th>
<th>Comparison</th>
<th>F-value</th>
<th>ndf</th>
<th>ddf</th>
<th>P-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Soyabean</td>
<td>MNR</td>
<td>0.1193</td>
<td>-0.0038</td>
<td>0.0013</td>
<td>-0.0003</td>
<td>0.29</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>LEG</td>
<td>0.1279</td>
<td>-0.0034</td>
<td>0.0017</td>
<td>-0.0003</td>
<td>0.30</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>CNV</td>
<td>0.1484</td>
<td>-0.0037</td>
<td>0.0022</td>
<td>-0.0009</td>
<td>0.04</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Soyabean</td>
<td>MNR</td>
<td>0.0083</td>
<td>-0.0005</td>
<td>0.0006</td>
<td>-0.0004</td>
<td>0.02</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>LEG</td>
<td>0.0078</td>
<td>-0.0003</td>
<td>0.0013</td>
<td>-0.0003</td>
<td>0.11</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>CNV</td>
<td>0.0088</td>
<td>-0.0002</td>
<td>0.0044</td>
<td>-0.0011</td>
<td>0.08</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Fig. 4 Soyabean grain yield as a function of weed biomass across cropping systems using the modified rectangular hyperbola model (Eqn 1). All available plot-level data were used to construct plots (MNR n = 119; LEG n = 169; CNV n = 211). Cropping systems are represented by different lines: organic manure (MNR) = dotted line; organic legume (LEG) = dashed line; conventional (CNV) = solid line.

Fig. 5 Maize grain yield as a function of weed biomass across cropping systems using the modified rectangular hyperbola model (Eqn 1). All available plot-level data were used to construct plots (MNR n = 133; LEG n = 204; CNV n = 324). Cropping systems are represented by different lines: organic manure (MNR) = dotted line; organic legume (LEG) = dashed line; conventional (CNV) = solid line.
organic systems, higher weed biomass was not associated with concomitant reductions in yield to the degree that yields were associated with weed biomass in the CNV systems. Weed–crop competition relationships were not significantly different in soyabeans. However, the trend was similar to that of maize and indicated the relationship between soyabeans yield and weed biomass was weakest in the MNR, intermediate in the LEG and strongest in the CNV system.

Differences in row spacing and crop density between cropping systems may be partially responsible for the lack of significant differences in weed–crop competition in soyabeans. Because soyabeans were planted in 9 cm rows in the CNV system and 76 cm rows in the organic systems, the length of time until canopy closure was likely shorter in the CNV system. The duration of time from planting to canopy closure increases with wider row spacing, thus influencing the growth and development of both crop and weeds (Knezevic et al., 2003). For example, across a range of row spacing spanning from 19 to 76 cm, the critical period in the crop growth cycle when weed control must be initiated to protect potential yield loss was determined to be latest in 19 cm rows and earliest in 76 cm rows, illustrating a decrease in soyabeans competitive ability at wider row spacing (Knezevic et al., 2003).

The results for maize and soyabeans indicate an apparent increase in tolerance to weed competition in organic cropping systems and warrant additional research (Ryan et al., in press). Differential weed–crop competition relationships could be a result of differences in weed species composition among systems. Data regarding weed community composition were not collected in every year of the 27-year experiment; thus it is impossible to determine the extent to which weed compositional differences contributed to the differences in weed–crop competitive relationships observed in this experiment. Other possible mechanisms for the apparent increase in crop tolerance to weed competition in the organic systems could involve changes in soil resource quantity, quality or temporal availability that occur with increasing diversification of cropping systems and delayed planting (Liebman & Davis, 2000; Smith et al., 2008). In agreement with our results, Dyck et al. (1995) also observed that weed–crop interference in maize can depend on the fertility source (legume vs. mineral fertiliser).

These results suggest that previous research focused on quantifying weed–crop competitive relationships in simplified cropping systems (one or two crops and mineral fertiliser) may have limited applicability to more diversified and organically managed cropping systems. Additional research aimed at understanding how weed–crop competition relationships vary across different management systems may enhance our understanding of the impacts that weeds have on crop production and provide opportunities for developing more effective weed management strategies (Zimdahl, 2004). Studies that experimentally manipulate weed abundance and community composition across different management systems will likely be especially helpful in elucidating the generality of the differences in weed–crop competition relationships in organic and CNV cropping systems observed in this study (Ryan et al., in press).

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