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MAIZE-BASED LOW-INPUT CROPPING SYSTEMS CAN PROVIDE EFFECTIVE WEED CONTROL WHILE ENSURING CROP PRODUCTIVITY

S. GIULIANO (1), G. ADEUX (1,2), S. CORDEAU (2), J.-M. SAVOIE (3), L. ALLETTO (1)
(1) Université de Toulouse - École d'ingénieurs de Purpan, UMR 1248 AGIR – 75, voie du TOEC, BP 57611, F-31076 Toulouse cedex 3, France. simon.giuliano@purpan.fr
(2) INRA, UMR1347 Agroécologie, BP 86510, F-21000 Dijon, France.
(3) Université de Toulouse - École d'ingénieurs de Purpan, UMR 1201 DYNAFOR – 75, voie du TOEC, BP 57611, F-31076 Toulouse cedex 3, France.

ABSTRACT

Conventional Maize Monoculture (MM_{Conv}) is now questioned for environmental reasons. During a five-year field experiment, yield and weed pressure of MM_{Conv} was compared to three low-input Cropping Systems (CS) : MM_{LI}, a Low-Input Maize Monoculture; MM_{CT}, a Conservation Tillage Maize Monoculture; Maize-MSW, Maize rotated with Soyabean and Wheat, all designed to reduce water pollution. In 2014 and 2015, weed-free zones were established on all CS.

Weed biomass was higher in MM_{CT}, especially for spring grasses and perennials. MM_{Conv} (11.3±1.1 T ha^{-1}) and MM_{LI} (10.6±2.3 T ha^{-1}) had higher grain yields than MM_{CT} (8.2±1.9 T ha-1). Finally, concerning yields observed in weed-free zones, MM_{CT} yields were reduced by 2.1 T ha^{-1} respect to those on the other three CS, indicating that yields in MM_{CT} were not mainly impacted by weeds. The absence of difference between weed-free zones and the rest of the plot on all CS suggest that low-input CS were sufficiently efficient in managing weed pressure.

Keywords: Integrated weed management, cropping system experiment, maize, weed competition.

RÉSUMÉ

DES SYSTEMES DE CULTURE ALTERNATIFS A LA MONOCULTURE DE MAÏS EFFICIENTS POUR GERER LA FLORE SPONTANEE

La Monoculture de Maïs conventionnelle (MM_{Conv}) est remise en question du fait de ses impacts environnementaux. Ce système de culture (SdC) a été testé au champ pendant cinq ans et comparé à trois SdC (MM_{LI}, une MM à bas-niveau d'intrants; MM_{CT}, une MM en agriculture de conservation et Maize-MSW, un maïs en rotation avec soja et blé tendre) ayant pour objectif de réduire la pollution de l'eau. En 2014 et 2015, des zones sans adventice ont été mises en place sur tous ces SdC.

La biomasse adventice était plus importante sur MM_{CT}, en particulier pour les graminées estivales et les espèces pérennes. Les rendements de MM_{Conv} et de MM_{LI} étaient similaires, supérieurs à ceux de MM_{CT}. Dans les zones sans adventice, les rendements mesurés dans MM_{CT} étaient 2.1 T ha^{-1} inférieurs à ceux des trois autres SdC, indiquant que les rendements plus faibles de MM_{CT} ne sont pas, en premier lieu, la conséquence des adventices. L'absence de différence significative entre les zones sans adventices et le reste de la parcelle sur l'ensemble des SdC suggère que les SdC à bas niveau d'intrants ont été efficients pour gérer correctement la pression en adventices.

Mots-clés : Désherbage intégré des cultures, systèmes de culture, maïs, impact des adventices.

INTRODUCTION

Early emerging weeds, such as *Echinochloa crus-galli*, can generate important grain yield losses in maize (*Zea mays* L.) (Bosnic & Swanton, 1997). In conventional Maize Monoculture (MM), herbicides represent 78% of total pesticide applications (Aymard et al., 2014). Those applications can lead to weed resistance (Heap, 2014) as well as water pollution on extended maize production areas such as south-western France, especially when paired with irrigation and high nitrogen (N) fertilisation (Stoate et al., 2001). To reduce the negative externalities of conventional cropping systems, European and French authorities incite farmers to update their farming practices in order to reconcile environmental and economic performances. Consequently, in maize production, there is an increasing need to design Integrated Weed Management (IWM) cropping systems that remain profitable and in which weed control does not primarily depend on herbicides (Chikowo et al., 2009).

Since no individual alternative technique levels with the effectiveness of synthetic herbicides, IWM implements a wide combination of weed management tools with partial effects and a cropping system approach in order to achieve defined objectives (Liebman & Gallandt 1997).

Crop sequence is considered as one of the main IWM tools. While MM selects for summer and spring-germinating dicotyledonous (e.g. *Datura stramonium*) and grasses (e.g. *Echinochloa* sp., *Setaria pumila*), maize cropped in rotation with winter cereals selects for weed species capable of germinating during a wider time frame (e.g. *Fallopia convolvulus*, *Lolium* spp., *Sonchus asper*) (Fried et al., 2008) and reduces the number of dominant species (Chauvel et al., 2001).

Considering one defined crop rotation, such as MM, tillage is one of the major management filters that determines weed-species composition (Booth & Swanton, 2002). Conservation tillage should favour certain annual grasses and perennials (e.g. Zanin et al., 1997) and tends to result in higher weed density, biomass and diversity than conventionally tilled cropping systems (Buhler et al., 1994).

Curative weed management operations (herbicides applications and mechanical weeding) have also a major effect on weed flora composition. In-crop mechanical weeding, such as the rotary hoe, can engender high weed mortality rates (Van der Weide et al., 2008) and consequently, allows a reduction of herbicide use. Mixed-weeding, combining cultivation between rows and banded application of herbicide on rows, provides commercially acceptable weed control and crop yield (Leblanc et al., 1995). Weed management using cover crops, *via* the mechanisms of competition and allelopathy, can be effective but is influenced mainly by their biomass and dynamic of development (Blackshaw et al., 2007).

The present study evaluated the impact of low-input cropping systems on weed pressure, maize yield and the link between the latter two during a five-year cropping system experiment that tested three contrasted low-input cropping systems that had economic, environmental and social objectives.

MATERIALS AND METHODS

STUDY SITE

The field experiment was conducted at the Domaine de Lamothe – INP-EI PURPAN, Seysses, in south-western France (43.506 N, 1.237 E). The site is a flat field that was conventionally cropped with a sunflower (*Helianthus annuus* L.)/soft-wheat (*Triticum aestivum* L.) rotation during ten years before the establishment of the experiment. Therefore, it is assumed that the initial seedbank was homogeneous across the field. Maize crops in the experiment were first sown in spring 2011.

The soil is a stagnic Luvisol (IUSS, 2007) with an illuvial clay horizon at a depth of 35 to 60 cm. Spatial variations occur in soil texture in the arable layer, but was mostly silty-clay-loam (in average 40.9% silt, 33.4% clay and 19.5% sand). Mean annual precipitation on the five years of the experiment was relatively low (622 mm) but hydromorphy was frequent in spring. Hot and dry conditions occurred during summer (August is the hottest month, with a mean temperature of 21.8°C) and early autumn, while winters were mild (February is the coldest month, with a mean temperature of 5.7°C).

CROPPING SYSTEMS DESCRIPTION AND EXPERIMENTAL DESIGN

Three low-input cropping systems (two MM and a three-year rotation including maize) were compared with a conventional MM considered as the reference system. In addition to crop sequence, the three low-input cropping systems used various strategies that allowed to set objectives for reducing inputs (herbicides, water and N) compared to the reference conventional MM (Giuliano et al., 2016). For each cropping system, a set of decision rules was assigned for optimum management according to the objectives. The low-input cropping systems were designed and assessed to address agro-economic, social and environmental objectives, with a particular focus on the reduction of water pollution.

In terms of weed management, each system aimed at minimising the impact of weed flora on yield while respecting the set of objectives and constraints decided *ex ante* by experts. The intensity of herbicide use in a system was quantified with the "Herbicide Treatment Frequency Index" (HTFI), which is an indicator commonly used in Europe to measure the annual herbicide pressure on a plot (Brunet et al. 2008):

$$\boldsymbol{HTFI = \sum_T \frac{(Applied\ dose)_T\ x\ (Treatment\ area)_T}{(Approved\ dose)_T\ x\ Plot\ area}} \qquad [1]$$

where *T* = a given herbicide treatment, *Approved dose*, the homologated application rate of the given T herbicide on a crop for given targeted organisms, *Applied dose*, the effective application rate of the herbicide T and *Treatment area*, the surface of the plot concerned by the treatment.

Conventional Maize Monoculture (MM_{Conv})

This system was designed to maximise financial returns. It corresponds to the reference production system practiced across south-western France. Crop stress was avoided by using high levels of inputs (fertiliser, irrigation water and herbicides), similar to the regional means. The main agricultural operations consisted of spring mouldboard ploughing (25 cm deep) followed by combinations of cultivators and rotary harrowing (8 cm deep). The soil was bare during fallow period. Crop weed management depended primarily on broadcast preventive-herbicide spraying, in accordance with conventional practices. A curative remedial spray was performed occasionally, depending on the weed flora present at the 8-10 leaves stage. On average, during the five years of the experiment, the system had an HTFI of 2.2 and used 240 mm of irrigation water and 160 kg ha^{-1} of mineral N per year, amount that was calculated with the method of the nitrogen balance.

IWM Low-Input Maize Monoculture (MM_{LI})

This innovative maize cropping system aimed at protecting water quality by reducing nitrate and pesticide leaching by 50% and 70%, respectively. It was designed to reduce the use of fertiliser by 25% (through the use of a mid-early variety and the introduction of a cover-crop), HTFI by 50% through mixed weeding and irrigation by 25% through the use of an earlier variety than MM_{Conv}. These objectives were globally reached over the 2011-2015 period, with a mean HTFI of 0.8 and mean annual use of 132 kg ha^{-1} of mineral N and 184 mm of irrigation water. Soil and water protection were strengthened by using a cover crop, undersown in maize at 6-8 leaves stage buried by ploughing in spring. The economic objective of MM_{LI} was to maintain the same gross margin as MM_{Conv}.

Conservation Tillage Maize Monoculture (MM_{CT})

The main objective of this system was to reduce energy consumption and greenhouse gas (GHG) emissions by 40%. Other objectives included reducing pesticide leaching by 50%. To reach these objectives, conservation tillage practices were implemented: maize was either sown after strip tillage (2011-2012) or directly with no tillage (2013-2015) and a cover crop was sown immediately after maize harvest. Because of tillage type, weeds were chemically controlled with the objective to maintain the same HTFI as MM_{Conv} which revealed to be unachievable during the 2011-2015 period (HTFI of 3.1). Objectives for mineral N and irrigation water use were almost reached with respective annual means of 155 kg ha^{-1} and 203 mm while GHG emissions were reduced by 15%. Compared to MM_{Conv}, a slight decrease in gross margin was accepted because mechanisation costs were reduced.

Integrated maize rotation (MSW)

This system (MSW) corresponded to a three-year Maize-Soyabean (*Glycine max* (L.) Merr.)-soft Wheat (*Triticum aestivum* L.) rotation and was designed to reduce, at the rotation level, herbicide, irrigation and N inputs by 50% compared to those in MM_{Conv}. In this rotation, Maize (Maize-MSW) had the same input-reduction objectives as MM_{LI}, i.e. reducing the HTFI by 50% and the use of mineral N fertiliser and irrigation by 25%. During the 2011-2015 period, these objectives were reached for HTFI (1.0), mineral N use (132 kg ha^{-1}) and irrigation water use (182 mm). Maize-MSW aimed to maintain the same gross margin as MM_{Conv}. Each crop of the rotation was present every year on the experimental set-up.

Each system and each crop of MSW was randomised in two independent repetitions. Both plots in each system were managed identically: technical operations were performed the same day with the same amounts of inputs and resulted of a trade-off between the agronomic situations of both plots. Plot size was 720 m² (12 × 60m), in order to use farm-scale tools.

WEED SAMPLING

Weeds were identified to the species level but similar species, difficult to distinguish at the seedling stage were gathered. In further analysis, *Kickxia* spp. refers to *Kickxia spuria* and *Kickxia elatine*, *Polygonum* spp. refers to *Polygonum persicaria* and *Polygonum lapathifolium*, *Sonchus* spp. refers to *Sonchus oleraceus* and *Sonchus asper* and *Chenopodium* ssp. refers to *Chenopodium album* and *Chenopodium polyspermum*.

Weed densities (plants m^{-2}) were measured in quadrats (with size that varied from 1 m² to 0.25 m² during the experiment) at the 6-8 leaf stage of maize and maize flowering. In 2013, weed densities at the 6-8 leaf stage were not measured due to excess water and flooding in most of the plots.

Above-ground weed-species biomass (g DM m^{-2}) was assessed at the 6-8 leaf (in 2014 and 2015), flowering and maturity (both from 2011-2015) stages of maize. The biomass was collected according to defined rotating quadrats: two 1 m² quadrats (1.60 × 0.63 m) from 2011-2013 and then four 0.5 m² quadrats (1.60 × 0.32 m) on 2014 and 2015. Collected weed biomass was then dried (48 h at 80°C) and weighed. Data from the quadrats were averaged to obtain a plot-level measure of weed density and biomass.

INDICATOR OF WEED-PRESSURE RISK: THE POTENTIAL OF INFESTATION (PI)

Weed-density counts at the 6-8 leaf and flowering stages of maize were transformed into a "potential of infestation" (PI) indicator. It was calculated as the maximum density *d* over the *k* sampling dates of a given weed species *i* observed in a given quadrat *j* during one crop season (e.g. at both maize 6-8 leaf and flowering stages), which was then averaged over the n quadrats of the plot:

$$\mathrm{PI}_i = \frac{1}{n}\sum_{j=1}^{n} d\max(d1, d2, \ldots, dk) \qquad [2]$$

At the community level, PI could then be calculated each year as the sum of all PI_i calculated for each weed species. The PI indicator provides a global image of the weed flora capable of emerging, i.e. the worst-case scenario that could occur after weed control in a cropping system during a growing season. Compared to other indicators such as the commonly used average density, PI considers the maximum density thus, it is not biased by species time of emergence or time of sampling (Stoller & Wax, 1973). In addition, PI considers the average of maximum densities and not the maximum of all quadrat-date densities. Therefore, PI reduces the risk of overestimating weed density due to patchy distribution of weed species across the field (Hughes, 1990).

YIELD ASSESSMENT

Four 10-m² zones, consisting of two maize rows on 6.25 linear meters, were harvested in each plot to measure grain yield and grain moisture content. Grain yields were then standardised to a 15% grain moisture content.

In order to assess the impact of weeds on maize grain yield, in 2014 and 2015, weed-free zones were installed on each plot. They consisted of two 19.2 m² zones (3.2 m × 6 m) per plot that were hand-weeded weekly from sowing to maize harvest to assess the impact of weeds on yield in the rest of the plot. Yield in each weed-free zone was measured by harvesting a 1 m² (in 2014) or a 6 m² zone (in 2015).

STATISTICAL ANALYSIS

All observations and indicators were averaged at the plot level: two values per year and per system were available for each variable. Maize-MSW had as many observations as monocultures, i.e. ten observations over the five years, since all crops were cropped every year.

All weed biomasses and PI were log(x+1) transformed to stabilise variances. Means were then back-transformed for graphs. For all response variables Y, a linear regression was performed with the lm function in R software (R Development Core Team, 2011) on the overall dataset to identify system, block, year and potential interaction effects as follows:

$$Y_{ijkf} = \mu + system_i + year_j + block_k + system{:}year_{ij} + e_{ijkf} \qquad [3]$$

When the system:year interaction was significant, the dataset was then split into year-by-year sub-datasets and then analysed as follows:

$$Y_{ikf} = \mu + system_i + block_k + e_{ikf} \qquad [4]$$

ANOVAs were performed on results of each regression with the car package (Fox & Weisberg, 2011). When not significant, factors were removed from the model in hierarchical order (block, system:year and year) and the ANOVA was calculated again. If system and/or year effects were significant, the response variable was subjected to Tukey's Honest Significant Difference (HSD) test ($p < 0.05$) for multiple means comparisons with the agricolae package (de Mendiburu, 2014). Each variable's homoscedasticity and residues normality was tested with, respectively, a Bartlett and Shapiro-Wilk test with a p-value of 0.05 to reject the null hypothesis. When assumptions of the ANOVA were not met, data was analysed with a non-parametric Kruskal-Wallis test with a Bonferroni correction.

Evolution of PI of every species during the 5 year-experiment was determined by a Pearson's correlation coefficient between year and PI. Since Maize-MSW was only cropped twice on the same plots for two out of three sets of replicates, too few data were available to calculate these coefficients (i.e. 4 observations). Pearson's correlations were also calculated between maize grain yield and weed biomass.

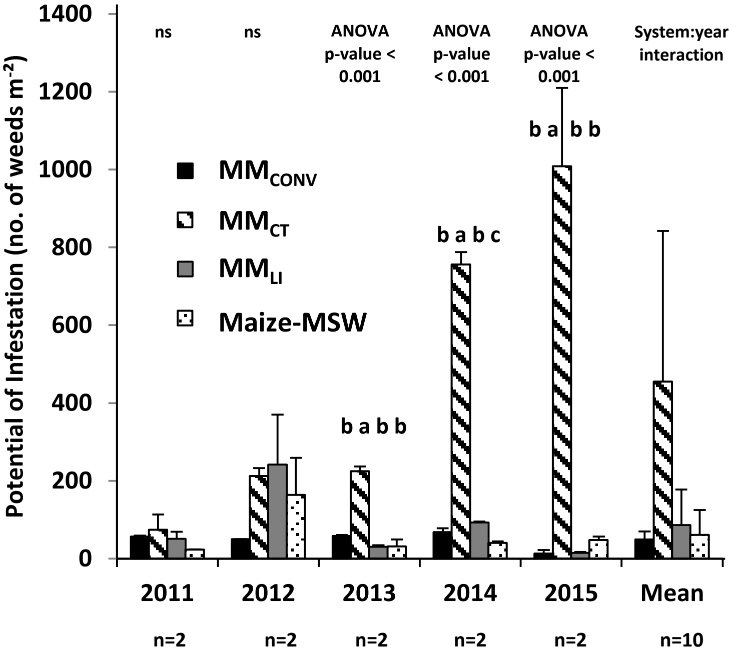
RESULTS

COMPARAISON OF WEED COMMUNITY POTENTIAL OF INFESTATION AMONG CROPPING SYSTEMS

Year (*$p<0{,}001$*), system (*$p<0{,}001$*) and system:year interaction (*$p<0{,}001$*) had an effect on weed community PI. Yearly PI differences between cropping systems were not observed until 2013 (Fig. 1). In 2013 and 2015, PI of MM_{CT} (224±12 plants m^{-2}, 1008±202 plants m^{-2}) was always greater than the PI of MM_{Conv} (59±3 plants m^{-2}, 13±8 plants m^{-2}), MM_{LI} (31±4 plants m^{-2}, 15±3 plants m^{-2}) and Maize-MSW (31±19 plants m^{-2}, 48±8 plants m^{-2}). In 2014, PI in Maize-MSW (41±4 plants m^{-2}) was significantly lower than PI of MM_{CT} (756±32 plants m^{-2}), MM_{Conv} (68±10 plants m^{-2}) and MM_{LI} (93±3 plants m^{-2}).

Figure 1 : Comparison of annual potential of infestation (PI, see equation [2] for details) among the four cropping systems (2011-2015). Error bars represent standard deviations. Bars sharing the same letter are not significantly different at p<0,05 (Tukey HSD Test).

Figure 1 : Comparaison du potentiel d'infestation annuel (PI, voir équation) entre les quatre systèmes de culture. Les barres d'érreurs représentent l'écart-type. Les barres partageant la même lettre ne sont pas significativement différentes à p<0,05 (Test de Tukey HSD).



EVOLUTION OF WEED SPECIES POTENTIAL OF INFESTATION AMONG CROPPING SYSTEMS

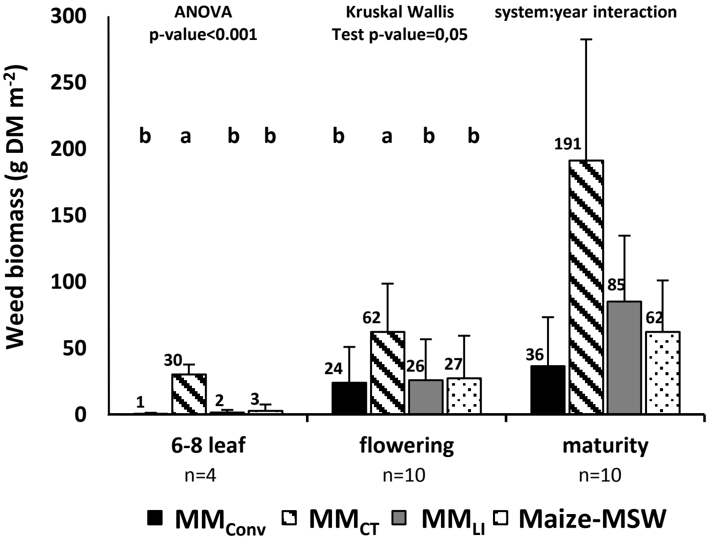
Pearson's correlation coefficients were computed and tested to determine if PI of weed species in a given cropping system evolved significantly during the experiment. Most correlations were not significant. Total PI evolved significantly only in MM_{CT}, increasing from 74±39 plants m^{-2} in 2011 to 1008±202 plants m^{-2} in 2015 (Fig. 1). This evolution can mainly be explained by the evolution of *E. crus-galli* ($p<0,001$) in MM_{CT} (3±1 plants m^{-2} in 2011 to 935±218 plants m^{-2} in 2015). Other species significantly evolved but did not affect management strategies: *Sonchus* spp. in MM_{Conv} (from 3±1 plants m^{-2} in 2011 to 8±4 plants m^{-2} in 2015), *C. arvensis* in MM_{Conv} (from 5±1 plants m-2 in 2011 to 0±0 plants m^{-2} in 2015) and *Solanum nigrum* in MM_{CT} (from 1±0 plants m^{-2} in 2011 to 0±0 plants m^{-2} in 2015).

COMPARISON OF WEED COMMUNITY BIOMASS AMONG CROPPING SYSTEMS

System had a significant effect on weed biomass at the 6-8 leaf stage ($p<0.001$)and at maize flowering ($p=0.05$) and system:year interactions were observed for weed biomass at maize maturity ($p<0.01$). At the 6-8 leaf stage (2014-2015), mean weed biomass in MM_{CT} (30±7 g DM m^{-2}) was significantly greater than in the other cropping systems ($p <0.001$), which were almost weed-free (Fig.2). At maize flowering, mean weed biomass in MM_{CT} (62±36 g DM m^{-2}) was still significantly greater than in the other cropping systems (Kruskal-Wallis test, $p=0,05$).Year-to-year analysis at maize maturity revealed differences in weed biomass among the cropping systems in 2011 and 2015. In 2011, weed biomass at maize maturity was greater in MM_{LI} (117±29 g DM m^{-2}) than in MM_{Conv} (52±15 g DM m^{-2}), and was not significantly different from the two latter in MM_{CT} (87±14 g DM m^{-2}) and Maize-MSW (84±4 g DM m^{-2}). In 2015, weed biomass at maize maturity was greater in MM_{LI} (91±69 g DM m-2) and MM_{CT} (181±109 g DM m^{-2}) than in MM_{Conv} (3±2 g DM m^{-2}), that could not be distinguished from the three latter for Maize-MSW (20±10 g DM m^{-2}).

Figure 2 : Mean weed biomass at three stages of maize growth among the four cropping systems (2011-2015). Weed biomass at the 6-8 leaf stage was sampled only in 2014 and 2015. Error bars represent standard deviation. Bars sharing the same letter are not significantly different at p<0,05 (Tukey HSD)

Figure 2 : Comparaison de la biomasse adventice moyenne à trois stades physiologiques du maïs entre les quatre systèmes de culture. La biomasse adventice au stade 6-8 feuilles n'a été collectée qu'en 2014 et 2015. Les barres d'érreurs représentent l'écart-type. Les barres partageant la même lettre ne sont pas significativement différentes à p<0,05 (Test de Tukey HSD).



COMPARISON OF WEED SPECIES BIOMASS AMONG CROPPING SYSTEMS

Significant differences in mean weed species biomass were observed among the cropping systems at maize maturity (2011-2015). The biomass of annual grasses was greater in MM_{CT} (data not shown) mainly because *E. crus-galli* ($p<0,001$) had a more important biomass in this system (140±114 g DM m^{-2}) than in MM_{Conv} (6±7 g DM m^{-2}) and Maize-MSW (14±21 g DM m^{-2}), and was not significantly different than the three latter in MM_{LI} (25±29 g DM m^{-2}). *Digitaria sanguinalis* (Kruskal Wallis test, $p<0,01$) and *S. pumila* (Kruskal Wallis test, $p<0,01$), two other annual grasses, also had a more important biomass in MM_{CT} (4±11 g DM m^{-2}, 2±0 g DM m^{-2}) than in MM_{Conv} (0±0 g DM m^{-2}, 0±0 g DM m^{-2}). The main perennial species, *C. arvensis*, had also greater biomass (Kruskal Wallis test, $p<0,01$) in

MM_{CT} (4±3 g DM m^{-2}) than in MM_{Conv} (1±1 g DM m^{-2}), and could not be distinguished from the two latter in MM_{LI} (2±3 g DM m^{-2}) and Maize-MSW (2±3 g DM m^{-2}). The biomass of annual broadleaf species did not differ significantly among the systems (data not shown), but *Chenopodium* spp. biomass was higher in MM_{LI} (4±5 g DM m^{-2}) than in Maize-MSW, in which it was almost absent (0±0 g DM m^{-2}), and was not significantly different than the two latter in MM_{Conv} (1±3 g DM m^{-2}) and MM_{CT} (1±3 g DM m^{-2}).

IMPACT OF WEEDS OF MAIZE YIELDS

Correlation analysis revealed that weed biomass had a significant and negative relation with grain yields : weed biomass at maize maturity and grain yield had an intense relationship (ρ =-0.62, p < 0.001). However, the analysis of weed free zones did not reveal an effect of weeding regimes (weed-free zones versus "normal" plot) on maize grain yields in 2014 and 2015.

COMPARISON OF MAIZE YIELDS AMONG CROPPING SYSTEMS

Year ($p<0.01$) and cropping system ($p<0.001$) had a significant effect on maize grain yields. Maize grain yields were lower in 2013 (7.8±2.4 T ha^{-1}) than in 2011 (10.4±1.4 T ha^{-1}), 2014 (10.6±1.9 T ha^{-1}) and 2015 (10.9±12.9 T ha^{-1}) and were not significantly different from the four latter in 2012 (10.0±23.8 T ha^{-1}). Maize grain yields were greater in MM_{Conv} (11.3±1.1 T ha^{-1}) and MM_{LI} (10.6±2.3 T ha^{-1}) than in MM_{CT} (8.2±1.9 T ha^{-1}) and were not different from the three latter in Maize-MSW (9.7±2.0 T ha^{-1}). Yield variability was greater in all three low-input cropping systems, particularly due to poor overall cropping system performances that lead to lower yields in 2013 (MM_{LI}: 7.8±2.8 T ha^{-1}; MM_{CT}: 5.9±0.4 T ha^{-1}, Maize-MSW: 6.5±0.5 T ha^{-1}) than those in MM_{Conv} (11 ± 2.1 T ha^{-1}), which was the only system ploughed that year.

DISCUSSION

EFFICIENT WEED MANAGEMENT IN MONOCULTURES WITH PLOUGHING

The combination of farming practices used in MM_{Conv}, such as annual mouldboard ploughing (Roger-Estrade *et al.,* 2001), intensive use of pre-emergence herbicides (Pannacci et al., 2007) followed by one or two remedial sprays (Streit et al., 2002), known to be efficient weed-management tools, was effective. However, this reference cropping system is challenged by its environmental and long-term risks, such as soil erosion due to bare soil in winter (Stoate *et al.*, 2001), herbicide resistance (Heap, 2014), high pesticide leaching (Alletto *et al.*, 2013) and high greenhouse gas emissions (Giuliano *et al.*, 2016).

MM_{LI} was also a high-yielding cropping system, even though it was more variable than MM_{Conv}. Yields were reduced in 2013, probably due to wet conditions that did not allow mouldboard ploughing. Weed pressure, and particularly PI, was also more variable than in the reference system (MM_{Conv}). However, differences between these two cropping systems are not as large when one compares weed biomass at maturity – an integrative indicator to measure weed pressure (Primot *et al.*, 2006). Indeed, MM_{LI}'s decision rules consisted of curative weeding only when necessary; therefore, this decision rule could lead to higher weed density and, thus, PI. Yet, weed biomass at maize maturity did not differ between MM_{Conv} and MM_{LI} because the late inter-row mechanical weeding operations, occasionally paired with chemical sprays on the rows, effectively controlled weeds as noted by Leblanc *et al.* (1995).

Despite differences in weed management, both cropping systems generated similar weed communities. The main weed species were grasses such as *E. crus-galli,* and forbs such as *Polygonum* spp. and *Kickxia* spp.*,* all well-known species in maize-based crop rotations (Zanin *et al.*, 1997). Moreover, both cropping systems reduced the presence of *C. arvensis,* which is consistent with previous studies (Buhler *et al.*, 1994).

CONSERVATION TILLAGE

MM_{CT} showed lower and more variable maize yields than MM_{Conv}. Yields were particularly reduced in 2012 and 2013, which were the second and third years after the last mouldboard ploughing. The transition phase to conservation tillage was abrupt, not leaving enough time for biological activity and cover crops to replace the effect of ploughing, which resulted in higher soil compaction. Reduced maize yields under conservation tillage have been referenced (Van den Putte *et al.*, 2010) but are not consistent across the world (Pittelkow *et al.*, 2015) according to the pedo-climatic conditions and the cropping system studied.

MM_{CT} required greater herbicide use to compensate the absence of pre-sowing herbicide or mechanical weeding techniques. Higher weed infestation is recorded in conservation tillage agriculture (Buhler *et al.*, 1994), even though it is not always accepted (Murphy *et al.*, 2006) because no-till does not stimulate the soil seed bank. However, MM_{CT} PI increase's across was not significantly correlated with a higher weed biomass at maize maturity, which was steady from 2012 to 2015. This result suggests that competition between weeds occurs above a certain density.

Along with higher weed pressure, the weed community in MM_{CT} shifted towards annual grasses (*E. crus-galli*, *D. sanguinalis* and *S. glauca*), which completely dominated after the first two years of the experiment, as reported in previous studies (Stoate *et al.*, 2001). Grasses are adapted to conservation agriculture because no-till maintains weed seeds on the soil surface, where annual grass seeds are able to germinate (Cordeau *et al.*, 2015). *C. arvensis*, a perennial broadleaf, most likely benefited from this system due to minimal soil disturbance (Zanin *et al.,* 1997).

ROTATING MAIZE

Maize yields were quite high in the MSW cropping system and were similar to those of MM_{LI} and MM_{Conv} if one ignores 2013, the year both plots in this system were flooded for two months after sowing. Even though the literature emphasises that crop rotation increases maize yield (Bullock, 1992), it was not the case in this experiment. This is most likely because, here, maize management in the rotation differed from that in the reference monoculture (MM_{Conv}): reduced N fertilisation, irrigation and chemical sprays. However, in 2015, Maize-MSW was the highest yielding cropping system with 12.2±0.3 T ha^{-1}. This suggests that low-input cropping systems with diversified rotations could generate long term productivity along with environmental benefits (water quality and quantity, energy use).

Maize-MSW had a low HTFI because of the efficiency of the main agronomic tools implemented: rotation (Fried *et al.*, 2008), mouldboard ploughing before maize (Buhler *et al.*, 1994), mechanical weeding (Van der Weide *et al.*, 2008) and chemical spraying centred on the crop row (Leblanc *et al.*, 1995). Moreover, it obtained good results for all weed-management indicators: PI and weed biomass were similar to those of MM_{Conv} and were slightly lower than those of MM_{LI}, which used a similar strategy to manage the crop, apart from crop rotation. This could indicate that Maize-MSW benefits from an additional rotation effect. Even though their percentages differed, the main weed species were similar in Maize-MSW and in MM_{Conv} and MM_{LI}. It can be hypothesised that, for a given crop type, mouldboard ploughing influence weed-flora composition more than all other techniques used to manage weeds, including crop rotation as suggested by Fried *et al.* (2008).

WEED FREE ZONES AND MAIZE YIELD

The weed-free zones established in 2014 help to better understand the link between weeds and yield loss. Across all cropping systems and years, a mean reduction in yield of 0.8 T ha^{-1} (*NS*) was observed between the weed-free zones and the rest of the plot, even though weed biomass at maize maturity was high in some cropping systems, as in $MM_{CT.}$ Indeed, no correlation was observed between yield loss and weed biomass at maturity. This suggests that weeds (in 2014 and 2015) were sufficiently managed in all cropping systems and did not compromise productivity excessively. MM_{CT} had lower yields than the other cropping systems not because of higher weed pressure since an important yield gap exists between MM_{CT} and the three other cropping systems in weed-free zones (2.1 T ha^{-1} in average). This suggests that in this experiment the influence of conservation agriculture on maize grain yields was greater than the impact of weed pressure.

CONCLUSION

Two of the three innovative cropping systems which implemented various techniques (such as mechanical weeding, mixed weeding, cover-crop introduction, reduced input use, and crop rotation) had the same weed management success (in terms of PI and biomass) and similar crop yields as the maize monoculture reference system. The lower maize yield in conservation tillage could not be attributed to higher weed pressure, even though the latter was higher than in the other systems. Overall, results show that IWM cropping systems are efficient at properly managing weeds while maintaining grain yield; thus, they encourage farmers to innovate their cropping systems for environmental benefits without fear of low agronomic performance.

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