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MAIZE-BASED CROPPING SYSTEMS TO REDUCE THE USE OF HERBICIDES AND IMPROVE WATER DRAINAGE QUALITY

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ABSTRACT

Conventional Maize Monoculture (MM_{Conv}) is partly responsible for water pollution by herbicides. Between 2011 and 2017, four alternative cropping systems (CS) were experimentally compared to a MM_{Conv}. They mobilized a gradient of rotations, cover crops, herbicides and tillage. Drainage and herbicide leaching were monitored with lysimetric plates on an experimental station (INP-PURPAN – Seysses – France).

Despite an annual variability, important contrasts appeared between CS, especially in terms of total amount of herbicide leaching. CS with reduction of herbicide use (-62 to -67%) had lower herbicides losses (-63 to -95%) than MM_{Conv} (3.4 g ha^{-1}). CS in conservation tillage tripled their herbicide leaching, due to punctual drainage events with important herbicides concentrations (up to 28 µg L^{-1} for a single molecule).

Keywords: lixiviation, systemic approach, weeding, environmental impact

RESUME

La monoculture de maïs conventionnelle (MM_{Conv}) est en partie responsable de pollution de l'eau, en particulier due aux herbicides. Entre 2011 et 2017, quatre systèmes de culture (SdC) alternatifs ont été comparés expérimentalement à une MM_{Conv}. Ils mobilisaient un gradient de rotation de cultures, de cultures intermédiaires, d'usage des herbicides et de travail du sol. Le drainage et la lixiviation des herbicides étaient suivis par des plaques lysimétriques en station expérimentale (INP-PURPAN – Seysses).

Malgré une variabilité annuelle, des contrastes importants apparaissent entre SdC, notamment en termes de quantité totale d'herbicides lixiviés. Les SdC avec réduction de l'usage des herbicides (-62 à -67%) ont eu des pertes d'herbicides beaucoup plus faibles (-63 à -95%) que MM_{Conv} (3.4 g ha^{-1}). La lixiviation des herbicides a triplé sur les SdC en réduction de travail du sol, dû à des événements drainants ponctuels avec des concentrations d'herbicides allant jusqu'à 28 µg L^{-1} pour une molécule.

Mots-clés : lixiviation, approche systémique, désherbage, impact environnemental.

INTRODUCTION

Maize cropping systems in south-western France

Maize is the second major crop in France, spread on approximately 3.0 million of hectares (Mha) to produce grain (12 Mt on 1.43 Mha), fodder (1.42 Mha) and seeds (64000 ha) (Agreste, 2017). It is a major crop for south-western France where is located around 40% of the national maize grain production (Chégut et al., 2018). In that region, maize is mainly cropped in short rotations or in monoculture, in 36% of the cases (Mercier-Poirier et Cassagne, 2010).

Due to dry and hot summers, grain maize remains the spreadiest irrigated crop in France, despite its surface reduced from 0.8 Mha in 2000 to 0.51 Mha in 2018 (Lerbourg, 2012; SAA, 2019). Irrigation is particularly spread in south-western France where up to 80% of the regional acreage of maize is irrigated with an average of 1820 m^3 ha^{-1} $year^{-1}$ of water supply (Agriscopie, 2016). This irrigation is important to improve profitability and to reach high yields (around 12 t DM ha^{-1}), around 3 t DM ha^{-1} more than in rainfed maize in the region (Chégut et al., 2018).

Other conventional maize cropping practices include an important mineral nitrogen fertilization (184 kgN ha^{-1}), a bare soil in winter with less than 15% of the total maize acreage of the region covered during the 6 months long intercrop in monoculture (Agreste, 2014) and a soil preparation based on mouldboard ploughing on around 80% of the cases (Agreste, 2017). Finally, this Cropping System (CS) can be characterised by its use of pesticide that is not particularly important in the overall (Treatment Frequency Index of 1.9, 50% less than wheat – Agreste 2014) but that is represented at 80% by herbicides often applied with an important quantity per hectare (e.g. homologated dose for S-metolachlor is 1920 g ha^{-1}, 1008 g ha^{-1} for dimethenamid-p).

Negative impacts of maize cropping on environment and water quality

The combination of the practices mentioned above results in negative impacts on various aspects of the environment (water, air, soil and biodiversity). Drived by a high mineral fertilizer use and an intensive ploughing, high CO_2 emissions are recorded on conventional maize CS (Giuliano et al., 2016). Pre-emergence herbicides can also volatilize in the air after application (Bedos et al., 2016) and maize monoculture is also known to reduce soil biodiversity (Garbeva et al., 2004).

Moreover, conventional maize monoculture threatens water quality since it can induce high nitrate and pesticides water concentrations in surface water. During the 2008-2015 period, 95% of south-western France water analyses made in rivers contained pesticide. Herbicides used exclusively or mostly on maize where largely represented: total metolachlor, deethylatrazine, bentazon, dimethenamid-p, acetochlor and nicosulfuron represented respectively the 2nd, 3rd, 5th, 6th, 7th and 8th molecules the most frequently detected, respectively from 45 to 10% of the cases, with concentrations up to 25 µg L^{-1} (AEAG, 2018). Important to note that, from those herbicides, uses of metolachlor (S-metolachlor is still authorized), and atrazine (from which deethylatrazine is the principal decomposition metabolite) were prohibited in 2004 while acetochlor was removed in 2014.

In maize production, herbicide applications occur early in the season – from April to June – while the crop is not or little developed and when intensive rain events, sometimes combined with irrigation, can occur (Ghidey et al., 2005). These excesses of water sometimes lead to important leaching and/or runoff events in field, according to the topography and soil characteristics. These leaching and runoff events then induce a transfer of herbicide in surface water. Nevertheless, the transfer of pesticide to surface water is very variable according to i) the physical properties of the molecule considered, ii) soil properties and iii) climate conditions during application and the following period. For example, in a

given environment, dicamba leaching changed from 0 to 5.6% of the applied dose, according to the rain distribution across the year and the type of tillage (Hall and Mumma, 1994).
To tackle down the problem of water contamination due to herbicide use on conventional maize production, several agroecological levers can be considered i) to reduce the use of herbicide and ii) limit their transfer to the surface water.
The use of crop rotation is one of the main levers to mitigate the impact of herbicides on the watershed. It reduces the frequency of application of the main herbicides that transfer into the surface water while it helps to better manage N and P fertilizers (Baffaut et al., 2019) and weed flora (Adeux et al., 2017), allowing a consecutive herbicide reduction.
However, introduction of crop rotation in maize is not always possible for the farmers. In that context, herbicide reduction application through mechanical and mixt weeding can be a valuable option (Giuliano et al., 2016). More specifically, banded applications of herbicide reduce between one third and two third the total amount applied on the field and was thus identified as efficient to reduce the transfer of herbicides in surface water (Lowery et al., 1998) even though these applications methods are poorly studied on their impact on water quality, especially in the case of mouldboard ploughing soil preparation.
Introduction of mulch tillage can be characterised by two major changes in the CS: i) a tillage reduction, also known as conservation tillage, that include a panel of tillage depth reduction and proportion of soil covered by residues, and ii) an introduction of a cover-crop terminated just before maize sowing. Tillage is known to affect water, and eventually containing pesticide, dynamic and distribution (Alletto et al., 2010). Moreover, cover crops residues affect other becoming processes of pesticides, especially sorption and degradation (Cassigneul et al., 2016). Furthermore, the increase content of organic matter in the topsoil layer can enhance the pesticide retention in that zone (Alletto et al., 2010). However, the few existing studies on mulch tillage influence on pesticide leaching remain unclear if mulch tillage enhances (Watts and Hall, 1996), maintains (Giuliano et al., 2016), or even reduces herbicide leaching respect to conventional tillage. Furthermore, little is known about pesticide leaching under innovative soil tillage such as strip tillage (Alletto et al., 2010).
Finally, mulch tillage can reduce soil transpiration and can thus, especially when combined with the use of earlier varieties, help to reduce irrigation water (Grassini et al., 2011) and thus reduce the risk of water drainage.
A rule-based CS approach is recommended to reach several somehow competing objectives of productivity, environmental quality and social wellness (Drinkwater, 2002). Applying the conceptual framework Efficiency-Substitution-Reconception (Hill and MacRae, 1995; Giuliano et al., 2016) in order to improve water drainage quality under economically performant maize based low-input CS is useful for combining together agroecological levers. The present study compares the performance of a conventional maize monoculture to four experimental CS that include several agroecological levers in order to reach the objective to protect water quality from herbicide pollution.

MATERIAL AND METHODS

The experiment took place at the Domaine de Lamothe—INP PURPAN, Seysses, Garonne Plain, south-western France (43.506N, 1.237E). The soil had an averaged soil texture in 0-30 cm layer of 33.4% clay (<0.002 mm), 40.9% silt (0.002–0.05 mm), and 19.5% sand (0.05–2 mm). However, spatial variations were observed between plots. See Giuliano et al. (2016) for more details on the site description.
From 2011 to 2017, four alternative CS were compared to a conventional maize monoculture (MM_{Conv}):

- MM_{Conv} was designed to get closer to the dominant practice in south-western France in order to maximize gross margin while limiting labour time. In order to avoid water stress, irrigation was not limited but managed with caution. A spring mouldboard ploughing followed by a rotary harrowing was performed after a bare soil during fallow period. After sowing, control of weeds was exclusively chemical with S-metolachlor and mesotrione used as pre-emergence broadcast application followed, 5 years out of 7, by a curative application composed of mesotrione, nicosulfuron and dicamba, according to the weed flora.
- MM_{LI}, a Low-Input Maize Monoculture aimed at reducing water pollution by pesticide leaching by 70%. To reach this objective, on the first hand, the use of herbicides was aimed to be halved while maintaining a similar weed pressure as MM_{Conv}. To reach these objectives, mechanical weeding and banded applications of herbicide on the seed row, at sowing and eventually during the row crop cultivation were introduced, with the same molecules used on MM_{Conv}. On the other hand, the use of irrigation water was aimed to be reduced by 25% respect to MM_{Conv} thanks to the introduction of an earlier variety. To improve soil and water protection, a winter cover crop (*Lolium hybridum* + *Trifolium* spp.) was implanted during fallow period. A mouldboard ploughing was performed in spring, both to bury the cover crop without herbicide and to ensure a good maize development. In 2013, a flood on the two MM_{LI} experimental plots prevented to plough in spring so reduced tillage was used and glyphosate was employed for cover-crop destruction.
- MM_{CT}, a Conservation Tillage Maize Monoculture that aimed at reducing pesticide leaching by 50% thanks to the introduction of a winter *Faba bean* L. based cover crop, a drastic reduction of tillage and the reduction of irrigation water. Maize was sown after a strip tillage in 2011 and 2012 then, since 2013, directly in a no-tillage management. To maintain an acceptable weed management, MM_{CT} weeds were exclusively chemically controlled with the objective to level the use of herbicides with MM_{Conv}. However, a different strategy was applied respect to MM_{Conv} since, from 2013, the use of S-Metolachlor was reduced in order to focus on a more efficient post-emergence weed control based on mesotrione, nicosulfuron and dicamba.
- MM_{Still}, a Strip Tillage Maize Monoculture that aimed at reducing pesticide leaching by 50% respect to MM_{Conv} thanks to the introduction of a permanent *Trifolium repens* L. cover from 2011 to 2013 than a winter *Sinapis alba* L. + *Vicia sativa* L. based cover crop. Moreover, respect to MM_{Conv}, tillage and irrigation water were reduced while herbicide used was aimed to be levelled. Every cropping season, two strip-tillage were realized between harvest and sowing, one in the late autumn and the other one in spring just before sowing in order to improve seed-bed preparation. In 2013, due to a too high competition with *Trifolium repens*, maize did not develop and thus was not harvested.
- Maize-MSW, a Maize rotated with Soybean and Wheat. An *Avena sp*. cover crop was sown after maize harvest while a *Sinapis alba* L. + *Vicia sativa* L. cover crop was sown after wheat. This CS was designed to reduce, at the rotation level, herbicide use and irrigation water by 50% compared to MM_{Conv}. In 2016, glyphosate was used before maize sowing since between ploughing (in November 2015) and maize seed bed preparation because ryegrass (*Lolium* sp.) was too developed for a mechanical destruction. Maize had the same input reduction objectives and the same management strategy as MM_{LI}, reducing the use of herbicides by 50% and the use of irrigation water by 25%. As for MM_{LI}, the objective was to reduce pesticide leaching by 70 %. Only results from the maize sequence of the rotation are presented here.

Each CS and each crop of the rotation was experimented every year on two 720 m² plots, each situated on two complete randomized independent blocs. Water drainage and pesticide leaching were monitored on each plot through a tension plate lysimeters (SIC300, UMS GmbH, Munchen, Germany) installed at 100 cm-depth. The tension was fixed in the plate lysimeter at −100 cm throughout maize cropping. Every year, the drainage monitoring started for all the plots at the same time, when water table was under 100 cm-depth, which occurred generally in May, before the first herbicide application, excepted in 2013 when plots were flooded in the beginning of June. During the cropping season and up until the plate lysimeters were not again submerged by the water table – usually until December – the water accumulated by the plate lysimeter was pumped thanks to a vacuum pump approximately every two weeks or as needed by the drainage volume. The leachate samples obtained were then kept at 4°C until analysis. Leachates with volumes above 50 mL (equivalent of 0.7 mm ha^{-1}) were susceptible to be analysed for all the pesticides applied on the plots previously in the cropping season. Both for technical (volume of the leachate) and economical (cost of the analysis) reasons, all the samples and all the molecules couldn't be analysed systematically. Thus samples and molecules were prioritized according to local expertise depending on importance of the molecules used in the CS, volume and timing of the leachate and previous results.

In this article, the cumulative water drainage per cropping season (in mm) was used to compare the CS and was calculated according to the following formula:

$$Water\ drainage = \frac{\sum_{i=1}^{k} Volume\ measured_i}{S}$$

Pesticide leaching was then quantified on each plot and calculated according to the following formula:

$$Herbicide\ leaching = \frac{\sum_{i=1}^{k} Concentration_i\ x\ Volume\ measured_i}{S\ x\ 100}$$

With *i* a given sample and *k* the number of samples per plot. Herbicide leaching is expressed in g ha^{-1}, Concentration is the pesticide concentration in µg L^{-1}. Volume measured is the volume of the sample in mL and S the surface of the lysimeter plate (0.075 m²).

Plots were the statistical unit. Since data did not assume a normal distribution, a non-parametric Kruskal-Wallis test followed by Steel-Dwass-Critchlow-Fligner multiple comparisons procedure were performed on the whole data set (*ie* all years and all CS included) but also, when indicated, on an annual basis. CS and year were the two factors that were tested independently.

RESULTS

Precipitations and irrigation per cropping system

The seven years of experimentations were contrasted in terms of amount (from 194 to 403 mm) and repartition of precipitations throughout the crop cycle. In consequence, irrigation water also varied greatly between years, according to the precipitations and their repartition. Irrigation water on MM_{Conv} was 229 mm, relatively close to the local means. MM_{LI} and Maize-MSW almost reached their objective to reduce by 25% the use of irrigation water with reductions of 21% and 19%, respectively while MM_{CT} (196 mm) and MM_{Still} (218 mm) slightly reduced their use respect to MM_{Conv} (Table I).

Table I: Amount of irrigation water per cropping season and per cropping system (mm) (Quantité d'irrigation par campagne et par système de culture (en mm))

	2011	2012	2013	2014	2015	2016	2017	**Mean**
MM_{Conv}	250	310	205	150	283	205	200	**229**
MM_{LI}	220	220	160	110	210	180	170	**181**
MM_{CT}	220	255	148	120	235	210	185	**196**
MM_{Still}	250	325	-	120	195	230	185	**218**
Maize-MSW	220	220	185	110	205	185	180	**186**
Annual mean	232	266	174	122	222	198	183	**200**

Drainage

Table II: Average number of water drainage events and mean annual water drainage recorded per CS from 2011 to 2017. Mean±standard deviation, a common letter indicates homogenous group according to a Kruskal-Wallis multiple comparison test, p<0.1 (Nombre moyen d'événements drainants et moyenne annuelle d'eau de drainage par systèmes de culture (SdC) entre 2011 et 2017. Moyenne±écart-type, une lettre identique un groupe homogène pour un test de Kruskal-Wallis, p<0.1)

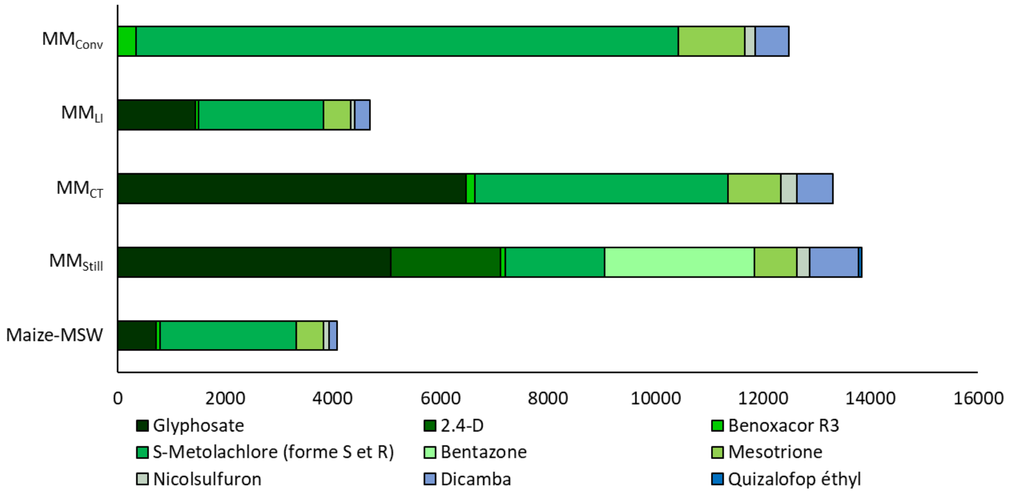
	Mean 2011-2017	
	number	**quantity**
MM_{Conv}	5.4 ±0.7 b	63 ±42 a
MM_{LI}	2.8 ±0.7 a	50 ±31 a
MM_{CT}	3.9 ±1.4 ab	55 ±39 a
MM_{Still}	5.1 ±1.4 b	91 ±55 a
Maize-MSW	3.3 ±0.7 ab	52 ±39 a

On average on all CS and all years, water drainage at 1-m depth was low, regarding both the number of events per year and the annual quantity, with respectively 4.1 events/year (e/y) and 62 mm. Important differences appear between years with 2011 and 2015, with respectively 1.3 and 2.5 e/y, recording significatively (Kruskal-Wallis test, $p<0.0001$) less drainage events than all the other years, ranging from 4.5 e/y (2016) to 5.4 e/y (2012). With 5.4 e/y, MM_{Conv} had significatively more drainage events than MM_{LI} (2.8 e/y) (Kruskal-Wallis test, $p=0.02$, Table II). The three other CS were intermediate. The quantity of water drained per year follows a similar pattern as the number of events with 2011 (19 mm) and 2015 (35 mm) recording less drainage than the four other years, ranging from 71 mm (2016) to 99 mm (2014). However, any significative difference appears between CS ranging from 50±31 mm for MM_{LI} to 91±55 mm for MM_{Still}.

Subsetting the data and considering only the years were drainage was higher (2012, 2013, 2014, 2016 and 2017), MM_{Still} (113 mm) shows a significatively higher drainage than MM_{CT} (67 mm), Maize-MSW (64 mm) and MM_{LI} (59 mm). In that case, MM_{Conv} is intermediate with 80 mm.

Quantity of pesticides applied

Figure II: Sum of the herbicide quantities applied on 2011-2017 per cropping system (g ha^{-1}) (Somme des quantités d'herbicides appliquées entre 2011 et 2017 pour chaque système de culture (en g ha^{-1}))



On the total of the seven years of experimentation, MM_{LI} and Maize-MSW, with respectively 4698 g ha^{-1} and 4078 g ha^{-1}, reduced by 62% and 67% the amount of pesticides applied respect to MM_{Conv} (12476 g ha^{-1}) and thus exceeded their initial objective to halve the use of pesticides (Figure 2). MM_{Still} and MM_{CT} did not entirely reached their objective to level the use of pesticides respect to MM_{Conv} with, respectively, 13837 g ha^{-1} (+11% compared to MM_{Conv}) and 13304 g ha^{-1} (+7%).

Herbicide concentrations in drainage water

Throughout the seven years and the five CS, 669 drainage measures were performed. They permitted to obtain 281 samples susceptible to be analysed (volume>50 mL). According to the molecules applied previously in the cropping season, the volume of the sample and the budget, 118 samples were analysed, with the same attention between CS.

Among these 118 samples, 36 came from MM_{Conv}, 29 from MM_{CT}, 25 from MM_{Still}, 15 from MM_{LI} and 13 from Maize-MSW. Maize-MSW and MM_{LI} had less sample analysed since they recorded less drainage events and had less pesticide applications that occurred latter in season.

7 of the 9 herbicides used on the CS (quizalofop-ethyl and 2,4-D were not analysed) and 3 degradation metabolites (AMPA - degradation metabolite from glyphosate), ESA and OXA - degradation metabolites from S-metolachlor) were analysed. Table III summarizes the global dataset on herbicides and their degradation molecules.

Table III: Maximum concentration, frequencies of detection, of samples with concentration>1µg L^{-1} and of samples with concentration>10µg L^{-1} and maximum concentration for the main herbicides used on the five CS

(Concentration maximale, fréquences de détection, d'échantillons avec concentration>1µg L^{-1} et d'échantillons avec concentration>10µg L^{-1} et concentration maximale mesurée pour les principaux herbicides utilisés sur les cinq SdC)

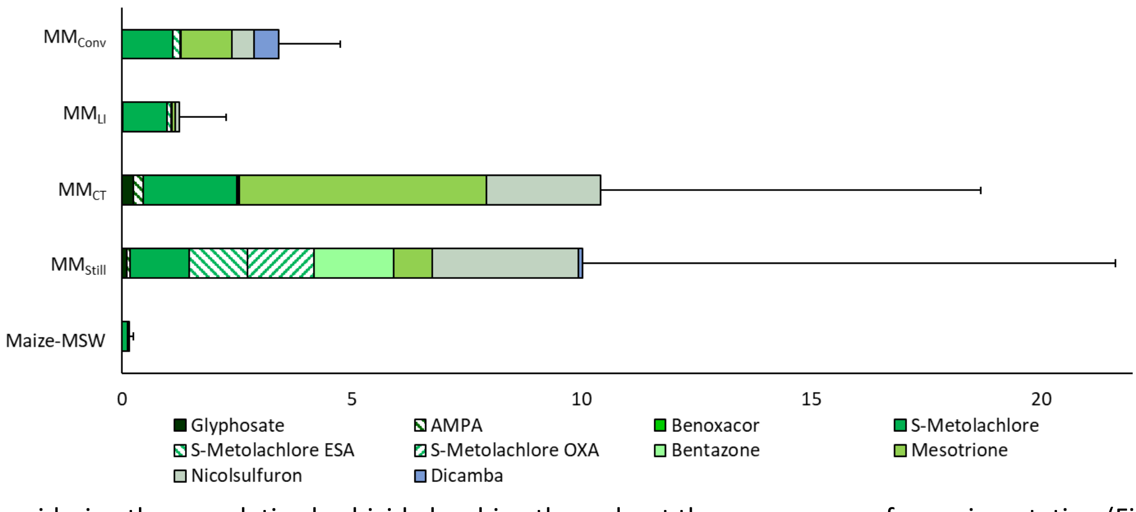
	bentazone	benoxacor	dicamba	glyphosate	AMPA	nicolsulfuron	mesotrione	s-metolachlor	ESA	OXA
number of analysis	5	39	27	35	30	69	94	61	5	5
detection frequency	100%	3%	37%	37%	40%	77%	82%	89%	100%	100%
frequency [C]>1µg L^{-1}	80%	0%	4%	3%	0%	20%	16%	26%	80%	60%
frequency [C]>10µg L^{-1}	20%	0%	4%	0%	0%	1%	2%	0%	20%	0%
max. [C] (µg L^{-1})	11.5	0.013	10.39	1.31	0.91	12.8	28.96	7.1	13.05	5.51

Important differences can be emphasized between molecules. Bentazone, ESA, OXA, and – to a lesser extent – S-metolachlor, mesotrione and nicosulfuron were detected in a large majority of the cases (from 100 to 77%) and were the ones the more detected at higher concentrations frequencies (above 1µg L^{-1} or 10 µg L^{-1}). On the other hand, glyphosate, AMPA, dicamba and especially benoxacor were detected in less than 40% of the cases. There are few samples with high concentrations.
Molecules can also be distinguished in terms of maximum of concentration with mesotrione, ESA, nicosulfuron, bentazone and dicamba having samples with concentrations above 10 µg L^{-1}.

Influence of cropping systems on herbicide leaching

Figure III: Mean cumulative herbicide leaching per cropping system on 2011-2017 (g ha^{-1}). The hatched traits correspond to the degradation metabolites of the active molecule situated on the left. The error bars represent the standard deviation (SD).

Moyenne de la lixiviation d'herbicide cumulée par SdC entre 2011 et 2017 (g ha^{-1}). Les traits hachurés correspondent aux métabolites de dégradation de la molécule mère située à la gauche. Les barres d'erreur représentent les écart-types.



Considering the cumulative herbicide leaching throughout the seven years of experimentation (Figure III), MM_{CT} (10.41 g ha^{-1}) and MM_{Still} (10.02 g ha^{-1}) were the CS that recorded more herbicide leaching, almost three times more than MM_{Conv} (3.40 g ha^{-1}). MM_{LI} and Maize-MSW had the lowest leaching recorded with respectively 1.25 g ha^{-1} and 0.16 g ha^{-1}. Herbicide leaching was very variable according to the blocs (SD bars-figure III). Very few events were responsible from the great majority of the leaching: in average, 3.5 events were enough to represent 90% of the leaching on MM_{Still}, 4 on MM_{CT}, 5.3 on MM_{Conv}, 2.7 on MM_{LI} and 0.9 on Maize-MSW.

Considering the cumulative annual leaching, Maize-MSW recorded significantly less pesticide leaching respect to MM_{Conv} (Kruskal-Wallis test, $p<0.1$). The three other CS were intermediate and not statistically different from MM_{Conv} and Maize-MSW.

DISCUSSION

Despite differences in irrigation management between CS, water drainage showed low significative correlation with irrigation water or total water (irrigation + precipitations) during the cropping season. Only MM_{LI}, the less irrigated CS, recorded significantly less drainage events than MM_{Conv}. However, water drainage quantity did not differ significatively between the five CS probably since i) water conductivity is highly influenced by two factors not contrasted between CS, soil texture (Jarvis and Messing, 1995) and rain intensity that led to an important annual and bloc variability (table II) – and ii) irrigation management on MM_{Conv} was also driven by tensiometers and an accurate expertise. Indeed, drainage recorded on MM_{Conv} (63±42 mm) is very low respect to other observations on conventional irrigated maize CS, where annual drainage could reach above 300 mm (Basso and Ritchie, 2005). Thus, the irrigation management on MM_{Conv} reduced the effect of irrigation on the four alternative CS.

The annual water drainage recorded was not correlated with herbicide leaching since the concentration in the leachate was very variable according when the period when drainage occurred. The highest leaching peaks were situated when intense drainage events occurred early in the cropping season, few days after herbicide spraying. This is emphasized by the fact that, across all CS, only 0.9 to 5.3 events on the 7 years were enough to explain 90% of the leaching.

In consequence, herbicide use, despite a high discrimination between CS (figure II), showed any correlation with herbicide leaching if observed molecule by molecule. For example, S-metolachlor application reduction on MM_{LI} respect to MM_{Conv} did not cause a reduction of S-metolachlor leaching. Nevertheless, CS impacted differently the water quality. The initial objectives of reduction by 70% of herbicide leaching is almost reached on MM_{LI} (-63%) and widely reached on Maize-MSW (-95%), which completes former results (Giuliano et al., 2016). On the other hand, the initial objective to halve herbicide leaching on MM_{CT} and MM_{Still} is far to be reached even if, due to the high early drainage event dependency of herbicide leaching, interaction between blocs, CS and years was very important (*e.g.* in 2014, herbicide leaching on MM_{CT} bloc 1 was 14.59 g ha^{-1} while it was 0.02 g ha^{-1} on bloc 2).

For MM_{CT} and MM_{Still}, the shift toward conservation tillage techniques implied to rely more often on other than S-metolachlor herbicide molecules (mesotrione, nicosulfuron and bentazone) that, even if used at low weight per hectare, have a higher susceptibility to drain due to their low potential to be adsorbed on organic matter and/or a higher solubility (PPDB, 2019). The highest Herbicide Treatment Frequency Index on those CS (HTFI is 2.3 on MM_{Conv}, 2.8 on MM_{Still} and 3.0 on MM_{CT}) induced a more frequent risk of having significative herbicide leaching events. Finally, conservation tillage techniques favour biological macropores (*e.g.* dead roots, worm galleries) in the soil that can induce preferential water flows throughout the cropping season, responsible for high drain flows. This study confirms, in maize-based CS, the higher risks of diffuse pollution due to highly concentrated pesticide leaching events in conservation tillage CS when they level or even rise the use of herbicide (Dairon et al., 2017). However, studies on the long term (>20 years) are needed to follow soil structure, water conductivity and consecutive pesticide leaching evolution under these conditions. As an example, on the last two years of the experiment (2016 and 2017), cumulative herbicide leaching on MM_{Conv} reached 1.71 g ha^{-1} while it was 0.44 g ha^{-1} for MM_{CT}.

On the other side, two CS, MM_{LI} and Maize-MSW, greatly reduced the herbicide leaching observed, probably due to a positive combination of mouldboard ploughing, a drastic herbicide use reduction, introduction of winter cover crops, irrigation management that limited drainage events and mechanical weeding. That combinatino limited the transfer risks. From that point of view, these two CS – or part of these CS adapted to a different context – could be deployed more widely on the territory, since they reach other economic, environmental and social objectives (Giuliano et al., 2016).

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