THÈSE

En vue de l'obtention du

DOCTORAT DE L'UNIVERSITÉ DE TOULOUSE

Délivré par :

Institut National Polytechnique de Toulouse (Toulouse INP)

Discipline ou spécialité :

Agrosystèmes, Écosystèmes et Environnement

Présentée et soutenue par :

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le mardi 6 juin 2023

Titre :

Evaluation multicritère des performances de systèmes de culture maïsicoles alternatifs à la monoculture de maïs conventionnelle et à faible impact sur l'environnement

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Ecole doctorale :

Sciences Ecologiques, Vétérinaires, Agronomiques et Bioingénieries (SEVAB)

Unité de recherche :

AGroécologie, Innovations, TeRritoires (AGIR)

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Evaluation multicritère des performances de systèmes de culture maïsicoles alternatifs à la monoculture de maïs conventionnelle et à faible impact sur l'environnement



Simon Giuliano, *Evaluation multicritère des performances de systèmes de culture maïsicoles alternatifs à la monoculture de maïs conventionnelle et à faible impact sur l'environnement*, 2023

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Université de Toulouse, Institut National Polytechnique de Toulouse, école doctorale SEVAB

Laboratoire

UMR 1248 AGIR INRAE-INP Toulouse

Financement

Ecole d'Ingénieurs de PURPAN



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Remerciements

A l'heure de terminer la rédaction de cette thèse, il est temps de remercier les personnes sans qui celle-ci n'aurait pas pu avoir lieu.

Mes premiers remerciements vont vers les personnes qui ont mis en place ces systèmes de culture et collecté, dans les frimas de février, sous la canicule d'août ou dans les brumes de novembre, l'ensemble des données qui ont permis de réaliser cette thèse : François Perdrieux, Gaël Rametti, Cyrielle Deswarte, et une mention toute particulière à ceux qui font vivre avec entrain le dispositif depuis plus de deux ans, Valentin Deremetz, Hélène Martin et Mickaël Cazeneuve. Je remercie également la soixantaine de stagiaires qui se sont succédés depuis 2010 et qui ont patiemment distingué, à la lumière des néons du labo, la sétaire du panic. Je tiens également à remercier chaleureusement l'ensemble du personnel du campus de Lamothe qui permettent à ce dispositif longue durée de perdurer dans le temps.

Evidemment, ces travaux de recherche n'auraient jamais pu voir le jour sans le travail de Lionel Alletto pour imaginer ce dispositif un peu fou, se démener pour en trouver les financements, le lancer concrètement et m'avoir accompagné dans mes premiers pas de futur chercheur. Pour tout ça, merci.

Je tiens également à remercier l'ensemble de mes collègues et en particulier celles et ceux – actuels ou passés – du département « sciences végétales et agronomie ». Merci pour la solidarité dont vous faites preuve, je suis fier de faire partie de votre département ! Merci Adeline Bouvard pour le coup de pouce pour la conclusion de ce travail.

Je souhaite également remercier mes responsables hiérarchiques successifs qui m'ont accompagné, encouragé et soutenu avec constance dans mes travaux de recherche : Djamila Lekhal, Jean Daydé, Eric Latgé, Christine Claudon et Alban Jacques.

Mes remerciements sont également institutionnels et s'adressent à l'Ecole d'Ingénieurs de PURPAN qui a financé cette thèse et m'a permis de la réaliser – ainsi que les travaux qui l'ont précédée – dans de bonnes conditions. Mes remerciements vont également à l'UMR AGIR et en particulier à l'équipe VASCO qui m'a offert une ouverture scientifique et une culture de l'agronomie systémique depuis mes débuts en tant qu'ingénieur de recherche.

Dans le cadre de cette thèse, je remercie plus particulièrement mes directeurs de thèse, Jean Daydé et Philippe Debaeke, d'avoir accepté et pris le temps d'encadrer et de guider ce travail, notamment au cours de la rédaction du manuscrit. Je tiens également à remercier les membres de mon comité de pilotage pour m'avoir orienté de manière pragmatique dans ce travail et pour leur contribution significative au premier chapitre de cette thèse : Matthew Ryan, Stéphane Cordeau et Alban Jacques. Je tiens également à remercier Guillaume Adeux pour son travail si précieux sur le chapitre III.

Merci également aux membres de mon jury de thèse, Laure Mamy, Guillaume Martin, Lionel Alletto et plus particulièrement mes deux rapporteurs, Christian Bockstaller et Antonio DiTommaso, c'est un honneur pour moi de vous exposer mes travaux.

Je souhaite terminer ces remerciements par des remerciements plus personnels. Tout d'abord à mon groupe d'entraînement des fléchettes du SATUC de m'offrir des respirations hebdomadaires salutaires et nécessaires à mon équilibre. Je remercie ensuite l'ensemble de ma

famille et plus particulièrement mon frère et mes parents : vous avez tant contribué à me faire grandir, à m'ouvrir et à me porter de tout votre amour. Les collines varoises, les falaises du Verdon et les champs du Piémont ont été essentiels dans ma construction et dans mon éveil aux questions agricoles et environnementales. C'est grâce à vous que j'ai trouvé un équilibre et le courage de toujours faire « du mieux que je peux ». Merci.

Je termine ces remerciements par ceux adressés à mes deux amours et sources de bonheur au quotidien, sans qui rien ne serait possible : merci Mélanie, merci de me supporter, dans tous les sens du terme, et merci Flore. Vous êtes avec moi à chacun de mes pas.

Table des matières

INTRODUCTION GENERALE 1

CHAPITRE I – REVUE DE LITTERATURE DES SYSTEMES DE CULTURE MAÏSICOLES DANS LES PRINCIPAUX BASSINS DE PRODUCTION EN CLIMAT TEMPERE : CARACTERISTIQUES TECHNIQUES, IMPACTS ENVIRONNEMENTAUX ET PERSPECTIVES D'AMELIORATION 5

I. A POLARIZED MAIZE PRODUCTION DEDICATED TO FEED AND BIOFUELS 6

1. PRODUCTION AND PRODUCTIVITY 6
2. WELL-ESTABLISHED INTENSIVE MAIZE-BASED CROPPING SYSTEMS IN TEMPERATE CLIMATES 9

II. MBCS STAKES 18

1. PROFITABILITY 18
2. PRICE VOLATILITY 18
3. RESOURCES DEPLETION: QUANTITY AND QUALITY 19
4. SOIL COMPOSITION AND STRUCTURE 22
5. WATER QUALITY 23
6. AIR QUALITY 24
7. CLIMATE CHANGE 27

III. HOW TO LIMIT MBCS ENVIRONMENTAL IMPACTS AND IMPROVE ITS SUSTAINABILITY IN TEMPERATE CLIMATES? 30

1. TILLAGE REDUCTION 30
2. COVER CROPS AND INTERCROPPING 31
3. NUTRIENT AND WATER MANAGEMENT 32
4. MAIZE CULTIVARS 33
5. MECHANICAL WEEDING 33
6. CROP DIVERSIFICATION 35

CONCLUSION: A NEED FOR A GLOBAL APPROACH OF CROPPING SYSTEMS 37

CAS D'ETUDE - L'EXPERIMENTATION SYSTEMES DE CULTURE DE LAMOTHE 38

I. HISTORIQUE 40

II. PROJETS ET EVOLUTION DES PROBLEMATIQUES DE RECHERCHE 41

III. PLAN EXPÉRIMENTAL 45

IV. CONTEXTE PÉDOCLIMATIQUE 45

V. SUIVIS SCIENTIFIQUES 46

VI. PUBLICATIONS DE RANG A PRODUITES A PARTIR DE DONNEES ISSUES DU DISPOSITIF EXPERIMENTAL 48

CHAPITRE II - EVALUATION MULTICRITERE DE SYSTEMES DE CULTURE A FAIBLE NIVEAU D'INTRANTS ET IMPACT SUR L'ENVIRONNEMENT, ALTERNATIFS A LA MONOCULTURE DE MAÏS CONVENTIONNELLE 48

I. INTRODUCTION 54

II. MATERIALS AND METHODS 56

1. SITE DESCRIPTION 56
2. CROPPING SYSTEMS DESCRIPTION 57
3. EXPERIMENTAL DESIGN 61
4. CROP AND PLANT SAMPLING 61

5. Achievements of the objectives 64
6. Statistical analysis 65

III. RESULTS 66

1. Discrimination of the four cropping systems 66
2. Maize yield 67
3. Weed abundance and biomass 68
4. Nitrogen supply and nutrition 70
5. Cover crop production 72
6. Gross margin 72
7. Labour 72
8. Cumulative drainage and number of pesticides leaching events 73
9. Calculated energy use and GHG emissions 73

IV. DISCUSSION 75

1. MM_{Conv} 76
2. MM_{LI} 78
3. MM_{CT} 78
4. Maize-MSW 80

CONCLUSION 81

CHAPITRE III - IMPACTS DES SYSTEMES DE CULTURE ALTERNATIFS A LA MONOCULTURE E MAÏS CONVENTIONNELLE SUR LA DYNAMIQUE DE LA FLORE ADVENTICE ET INFLUENCE DE LA FLORE ADVENTICE SUR LE RENDEMENT 81

I. INTRODUCTION 87

II. MATERIALS AND METHODS 89

1. Study site 89
2. Cropping systems description and experimental design 89
3. Weed sampling 91
4. Indicator of weed-pressure: the Potential of Infestation (PI) 91
5. Yield assessment 92
6. Statistical analysis 92

III. RESULTS 94

1. Effect of cropping systems on weed communities 94
2. Potential of infestation 95
3. Weed population dynamics 97
4. Weed biomass: effect of cropping systems at different maize growth stages 98
5. Impact of weeds and cropping systems on maize yields 99

IV. DISCUSSION 101

1. Efficient weed management in low-input cropping systems 101
2. Conservation tillage 101
3. Rotating maize 102
4. Weed biomass at maturity and maize yield 103

CONCLUSIONS 104

CHAPITRE IV - IMPACT DES SYSTEMES DE CULTURE ALTERNATIFS A LA MONOCULTURE DE MAÏS CONVENTIONNELLE SUR L'UTILISATION DES HERBICIDES ET LA QUALITE DE L'EAU 104

I. INTRODUCTION 110

II. MATERIALS AND METHODS 113

1. Pedoclimatic context 113
2. Cropping systems description and comparison 115
3. Experimental design 118
4. Cropping system agronomic performances 118
5. Leachate collection and pesticide analysis 118
6. Characterisation of water dynamics 119
7. Data analysis 120
8. Multicriteria assessment 121

III. RESULTS 122

1. Agro-environmental evaluation 122
2. Main factors influencing herbicide concentration in drainage water (Table IV.4) 125
3. Drivers of herbicide losses by leaching 128

IV. DISCUSSION 132

1. What influences herbicide leaching in cropping systems? 132
2. Cropping systems multicriteria assessment (Table IV.6) 135
3. Considerations to evaluate cropping systems performance 139

CONCLUSION 140

CHAPITRE V - DISCUSSION GENERALE ET PERSPECTIVES DE RECHERCHE 140

I. MAIZE BASED-CROPPING SYSTEMS TOWARDS AGROECOLOGY 142

1. Main scientific advances permitted by the thesis 142
2. Contribution to agroecological transition of cropping systems 144

II. A NECESSARY CHANGE OF THE CO-DESIGN MBCS FRAMEWORK 145

1. In the objectives: production of ecosystem services to mitigate and adapt to climate change 145
2. In the design process: adapting the co-innovation framework applied to the agroecological transition of cropping systems 151
3. In the implementation: combination of on station, on farm and model studies 153
4. Crop models, a complementary tool to explore scenarios and to facilitate cropping system design 155

III. A MULTICRITERIA ASSESSMENT APPROACH INTEGRATING ECOSYSTEM SERVICES AND ENVIRONMENTAL IMPACTS 157

1. From co-design to evaluation 157
2. Quantification of ecosystem services 158
3. Impacts quantification of MBCS 159
4. Interpretation of evaluation results 161
5. For long term experiments: taking into account the temporal variability through the resilience analysis 162

IV. PERSPECTIVES DE RECHERCHE POUR LES EXPERIMENTATIONS LONGUE DUREE DE LAMOTHE 164

1. Evaluation dynamique des performances 164
2. Comprehension des processus 165
3. Indicateurs d'etat et de performance 165
4. Prise en compte des dimensions territoriales et mise au point et evaluation d'un systeme de culture en agriculture de conservation des sols 166

CONCLUSION 166

BIBLIOGRAPHIE 170

BIBLIOGRAPHIE INTRODUCTION, CHAPITRE I, CHAPITRE V ET CONCLUSION 171

BIBLIOGRAPHIE CHAPITRE II 195

BIBLIOGRAPHIE CHAPITRE III 201

BIBLIOGRAPHIE CHAPITRE IV ____ **203**

ANNEXES ____ ***208***

I. MATERIEL SUPPLEMENTAIRE – CHAPITRE II - EVALUATION MULTICRITERE DE SYSTEMES DE CULTURE AGROECOLOGIQUES ALTERNATIFS A LA MONOCULTURE DE MAÏS ____ **210**

II. MATERIEL SUPPLEMENTAIRE – CHAPITRE III - IMPACTS DES SYSTEMES DE CULTURE ALTERNATIFS A LA MONOCULTURE DE MAÏS CONVENTIONNELLE SUR LA DYNAMIQUE DE LA FLORE ADVENTICE ET INFLUENCE DE LA FLORE ADVENTICE SUR LE RENDEMENT ____ **216**

III. MATERIEL SUPPLEMENTAIRE – CHAPITRE IV - IMPACT DES SYSTEMES DE CULTURE ALTERNATIFS A LA MONOCULTURE DE MAÏS CONVENTIONNELLE SUR L'UTILISATION DES HERBICIDES ET LA QUALITE DE L'EAU ____ **226**

Table des illustrations

Figure 1: publications on maize-based and corn-based cropping systems (% of publication on environment is a 5-year moving average) _____ *2*

Figure 2: Illustration of the basin controversy in the regional newspaper "Ouest France" (Bonnardel, 2021). Legend says: "The basin opponents blame that the basins favour maize irrigation and the continuing of an agricultural management deleterious for water quality". _____ *3*

Figure 3: graphical representation of the outline of the thesis _____ *4*

Figure I.1: Main maize producers in the world in 2019 (FAOSTAT, 2021) _____ *6*

Figure I.2: Ecoclimatic Index of maize (Ramirez-Cabral et al., 2017) _____ *7*

Figure I.3: Map of maize production distribution in the United-States (USDA, 2022) _____ *9*

Figure I.4: Technical management of Maize in MBCS in US Corn belt _____ *10*

Figure I.5: The Chinese Corn Belt (Hu and Zimmer, 2013) _____ *11*

Figure I.6: Technical management of maize in double cropping system in North China Plain _____ *12*

Figure I.7: Map of maize production distribution in Europe (2010-2014 average) (USDA, 2015) _____ *14*

Figure I.8: Technical management of maize in continuous cropping system in Southwestern France _____ *15*

Figure I.9: Proportion of rainfed to irrigated maize yields in several European countries (grey bars) (Webber et al., 2018) _____ *16*

Table I.1: Main management strategies in an emblematic location of the three regions studied _____ *17*

Figure I.10: Evolution of price of maize and soybean in US from 1960 to 2021 (Schnitkey et al., 2021b) _____ *19*

Figure I.11: Evolution of price of maize and soybean in US from 1990 to 2021 (Schnitkey et al., 2021a) _____ *19*

Figure I.12: Main elements to characterize GHG emissions of MBCS, inspired from (Juarez-Hernandez and Sheinbaum Pardo, 2019) _____ *25*

Table I.2: Dashboard of performances of MBCS on major environmental stakes and their variability. On the Likert scales, red indicates a low performance of conventional MBCS, yellow/orange is an intermediate performance and green represent a good performance. The length of the arrow is an estimation of the variability of the performance. _____ *29*

Tableau C.II : les systèmes de culture mis en place sur le dispositif système longue durée de Lamothe. En gras, les systèmes de culture dont les résultats sont présentés dans les chapitres II, III et IV. En hachuré, les systèmes de culture avec réduction du travail du sol _____ *42*

Figure C.I : les systèmes de culture testés à Lamothe en 2023 _____ *43*

Figure C.2 : Rendements en maïs sur le système de référence du dispositif comparés à la moyenne régionale (Hermouet, 2023, communication personnelle) _____ *44*

Figure C.3 : plan d'expérience _____ *45*

Tableau C.2 : texture moyenne du site expérimental, teneur en matière organique et pH _____ *45*

*Figure C.4 : illustration du gradient d'argile présent sur le site expérimental (horizon 10-30 cm)*_____ *46*

*Figure C.5 : installation d'une plaque lysimétrique sur le dispositif*_____ *47*

Table II.1: Main characteristics of the topsoil layer (0-30 cm) in each cropping systems treatment. _____ *56*

Figure II.1: monthly precipitation and average temperature during the period of the experiment. _____ *57*

Figure II.2: Main characteristics of the cropping systems tested: agronomic, economic, environmental and social objectives and the main technical management operations. _____ *60*

Table II.2: Coefficients for the three canonical functions for the 8 system variables included in the canonical discriminant analysis _____ *66*

Figure 3: First and second principal components of the Canonical Discriminant Analysis (CDA) derived from 8 variables indicated on the Table 2. The confidences ellipses represent a 5% confidence interval around the data of each system. _____ *66*

*Table II.3: Grain yield on the four cropping systems for the three years (mean ± SD, letter indicates homogenous group according to a Tukey-HSD test, $p < 0.05$; lowercase letter indicates difference between system and uppercase letter indicates difference between years).*_____ *67*

*Figure II.4: Weed density (plants m^{-2}) (a), weed biomass (g m^{-2}) (b) and N offtake by weeds (kg N ha^{-1}) (c) in the four cropping systems, from 2011 to 2013. (error bars indicate standard deviation; letters indicate groups according to a Tukey-HSD test at $p < 0.05$)*_____ *69*

*Table II.4: Main indicators for nitrogen use for the four cropping systems on the three years. (mean ± SD, letter indicates homogenous group according to a Tukey-HSD test, $p < 0.05$; lowercase letter indicates difference between system and uppercase letter indicates difference between years). For N fertilization, no comparison was computed.*_____ *71*

Figure II.5: Components of energy use analysis by year and by system. _____ *74*

*Figure II.6: Spider diagram of the relative performances of the three low-input cropping systems (MM_{CT}, MM_{LI} and Maize-MSW) with respect to the performance of the conventional system (MM_{Conv}) across 10 indicators of sustainability.*_____ *75*

Table II.5: Achievements of the objectives assigned on the main characteristics and inputs of the four cropping systems, in average on the three years. _____ *77*

Figure III.1a. Correlation circle with the first two axes of principal component analysis performed for the matrix of plots (four cropping systems) and weed species (described by the "Potential of Infestation" indicator). Weed species are indicated by their EPPO codes (http://eppt.eppo.org). _____ *94*

Figure III.1b. Scatter diagram with the first two axes of principal component analysis performed for the matrix of plots (four cropping systems) and weed species (described by the "potential of infestation" indicator). Ellipses represent a 95% confidence interval for each cropping system (Maize-MSW: integrated maize rotation; MMConv: conventional maize monoculture; MMCT: conservation tillage maize monoculture; MMLI: low-input maize monoculture). _____ *95*

Figure III.2. Potential of infestation (PI, see equation for details) detailed for the three main weed species (mean values over the 5-year period, 2011-2015) in the four cropping systems (Maize-MSW: integrated maize rotation; MMConv: conventional maize monoculture; MMCT: conservation tillage maize monoculture; MMLI: low-input maize monoculture). Year and block were treated as random factors. Error bars represent standard deviations. Bars sharing the same letter are not significantly different (P < 0.05, Tukey HSD Test). _____ 96

*Table III.1. Weed species' potential of infestation (mean±sd, no. of plants m-2) of the four cropping systems (Maize-MSW: integrated maize rotation; MMConv: conventional maize monoculture; MMCT: conservation tillage maize monoculture; MMLI: low-input maize monoculture). For each weed species, mean values followed by the same letter are not different according to Tukey's HSD test (denoted with °) or Kruskal-Wallis test (denoted with +) (** P < 0.01, *** P < 0.001). _____ 97*

Table III.2. Evolution of the potential of infestation (PI, log10 transformed) with time (5 years of experiment) for each weed species in each cropping system (10 observations for each system over the 5-year experiment; MMConv: conventional maize monoculture; MMCT: conservation tillage maize monoculture; MMLI: low-input maize monoculture). Values represent the slope between time and weed species' PI (log10 transformed) in the different cropping systems. Block was treated as a random factor. Slopes were tested to significantly different from zero (P < 0.05, ** P < 0.01, *** P < 0.001, NA: not applicable, ns: not significant). _____ 97*

Figure III.3. Mean weed biomass (2011-2015) at three stages of maize growth in the four cropping systems (Maize-MSW: integrated maize rotation; MMConv: conventional maize monoculture; MMCT: conservation tillage maize monoculture; MMLI: low-input maize monoculture). Weed biomass at the 6-8 leaf stage was sampled only in 2014 and 2015. Year and block were treated as random factors. Error bars represent standard deviation. Bars sharing the same letter are not significantly different (P < 0.05, Tukey HSD Test). Sampling (days after sowing): 8 leaf (48-58), flowering (76-113), maturity (140-179)._____ 98

Table III.3. Biomass of weed species (mean±sd, g DM m-²) between the cropping systems (Maize-MSW: integrated maize rotation; MMConv: conventional maize monoculture; MMCT: conservation tillage maize monoculture; MMLI: low-input maize monoculture) at maize maturity (140-179 days after sowing). For each weed species, mean values followed by the same letter are not different according to Tukey's HSD test (denoted with °) or, when ANOVA assumptions were not met, the Kruskal-Wallis test (denoted with +) (P < 0.05, ** P < 0.01, *** P < 0.001). _____ 99*

Table III.4. Mean maize grain yield (mean±sd, at 15% moisture content, T ha-1) of the cropping systems (Maize-MSW: integrated maize rotation; MMConv: conventional maize monoculture; MMCT: conservation tillage maize monoculture; MMLI: low-input maize monoculture). For each cropping system, mean values followed by the same letter are not different according to Tukey's HSD test (P<0.05). _____ 99

Figure III.4. Mean maize grain yield (at 15% water content, T ha-1) in the presence or absence of weeds (weed-free zones, hand-weeded) assessed in 2014 and 2015 for each cropping system (Maize-MSW: integrated maize rotation; MMConv: conventional maize monoculture; MMCT: conservation tillage maize monoculture; MMLI: low-input maize monoculture). Error bars represent standard deviations._____ 100

Figure IV.1: Flow-chart of the experiment. The rectangles with red borders are the results presented in the article. Rectangles with light blue background represent data from the annual dataset. Rectangles with light pink background represent data data from the individual dataset. _____ 114

Figure IV.2: Ombrothermic diagram during the experiment (2011-2018). Data from Domaine de Lamothe automatic weather station. During the maize cropping season (approximately April-October) important plots flooding occurred in May 2013 (especially on Maize-MSW and on MM_{LI} that could not be ploughed that year), in May 2017 and in spring 2018 while severe dry springs occurred in 2011 and 2015. _____ 115

Figure IV.3: Schematic describing the five cropping systems tested in the experiment. MM_{Conv} is the conventional Maize Monoculture (MM), MM_{LI} is the low-input MM, MM_{CT} is the conservation tillage MM, MM_{Still} is the strip-

till MM and Maize-MSW is the Maize rotated with soybean and wheat. HTFI is the Herbicide Treatment Frequency Index. _____ *116*

*Table IV.1: Physicochemical properties of the molecules monitored during the study. All data from PPDB (2020) except Koc for S-metolachlor (EU COMMISSION, 2004) and dicamba (EFSA, 2011)*_____ *119*

Figure IV.4: Technical performance of the CS in 2011-2018. a: Mean grain yields at 15% grain moisture (t ha-1). b: Log+1 of weed biomass measured at maize flowering. c: Herbicide Treatment Frequency Index. d: Mean annual herbicide amounts applied (g ha-1). Error bars indicate the standard deviation. Letters on the mean value of a CS indicate groups according to a post-hoc Fisher-LSD test with α=0.05. For each CS, the light bars indicate the annual yields from 2011 to 2018 and the dark bar indicates the mean value on 2011-2018 period. _____ *123*

Table IV.2: Average number of water drainage events and mean annual water drainage recorded per CS from 2011 to 2018. Mean ± standard deviation, CS that do not share a common lower-case letter within a column are significantly different (Kruskal-Wallis test) at P ≤ 0.1 _____ *125*

*Table IV.3: Characteristics of the molecules recorded in the 130 leachates analysed on the five CS. [C] = concentration*_____ *125*

*Table IV.4: Linear regressions models computed to explain the leachate herbicide concentrations observed in the 130 samples studied (individual dataset). n indicates the number of leachates measured. The variables retained in the model have a white background. ↗ and ↘ indicate the meaning of the correlation. The p-values for the significance of a variable used in the model are presented as: *** <0.001, ** <0.01, *<0.05, °<0.1 and the significance level of the variables retained in the model with p-values>0.1 are indicated. For each molecule, the relative importance of the variable retained in each model is indicated with the percentage. Molecules in italics are the ones from which the residuals do not follow a normal distribution.*_____ *126*

*Table IV.5: Linear regressions models computed to explain the annual herbicide losses by leaching observed. The significance levels retained are: *** <0.001, ** <0.01, *<0.05. The meaning of the relationship is indicated with ↗ (positive) and ↘ (negative). The relative importance of the applied herbicide quantity is indicated with a percentage. Molecules in italics are the ones from which the residuals do not follow a normal distribution.* _ *129*

Figure IV.5: Regression of the influence of total annual drainage (after herbicide application) by estimated losses in herbicides by leaching. Note that the y-axis is logarithmic. _____ *130*

*Figure IV.6: Mean annual applied herbicide amounts (a) and herbicide losses by leaching (b) per cropping system on the 2011-2018 period (g ha-1). Error bars represent standard deviation (SD).*_____ *131*

*Table IV.6: Multicriteria assessment of cropping systems compared with the initial objectives. HTFI is the Herbicide Treatment Frequency Index. The meaning of the relationship indicates if the objective was overwhelmed (↗) or not reached (↘). Mean ± standard deviation.*_____ *137*

Figure V.1: Schematic representation of "N cycle" and related ecosystem services in contrasted MBCS _____ *146*

*Figure V.2: Average maize sowing dates in France for varieties of different precocities between 1986 and 2011 (ARVALIS, 2012)*_____ *150*

Figure V.3: Examples of indicators, ecosystem services and biophysical determinants that can be measured on a MBCS _____ *160*

*Figure V.4: Description of the four components of resilience, extracted from (Peterson et al., 2018)*_____ *162*

*Figure V.5 : Evolution du rendement au cours du temps pour six systèmes de culture mis en œuvre sur l'expérimentation longue durée de Lamothe (Deremetz, 2023, communication personnelle)*_____ *164*

Liste des abréviations principales

CC : Cover Crop

CS : Cropping System

DPSIR : Drivers, Pressures, State, Impact, Responses

ES : Ecosystem Services

ESR : Efficience Substitution Reconception

GHG : GreenHouse Gases

GM : Genetically Modified

MBCS : Maize-Based Cropping Systems

MM : Maize Monoculture/Monoculture de Maïs

N : Nitrogen

NUE : Nitrogen Use Efficiency

P : Phosphorus

SdC : Système de Culture

TFI : Treatment Frequency Index

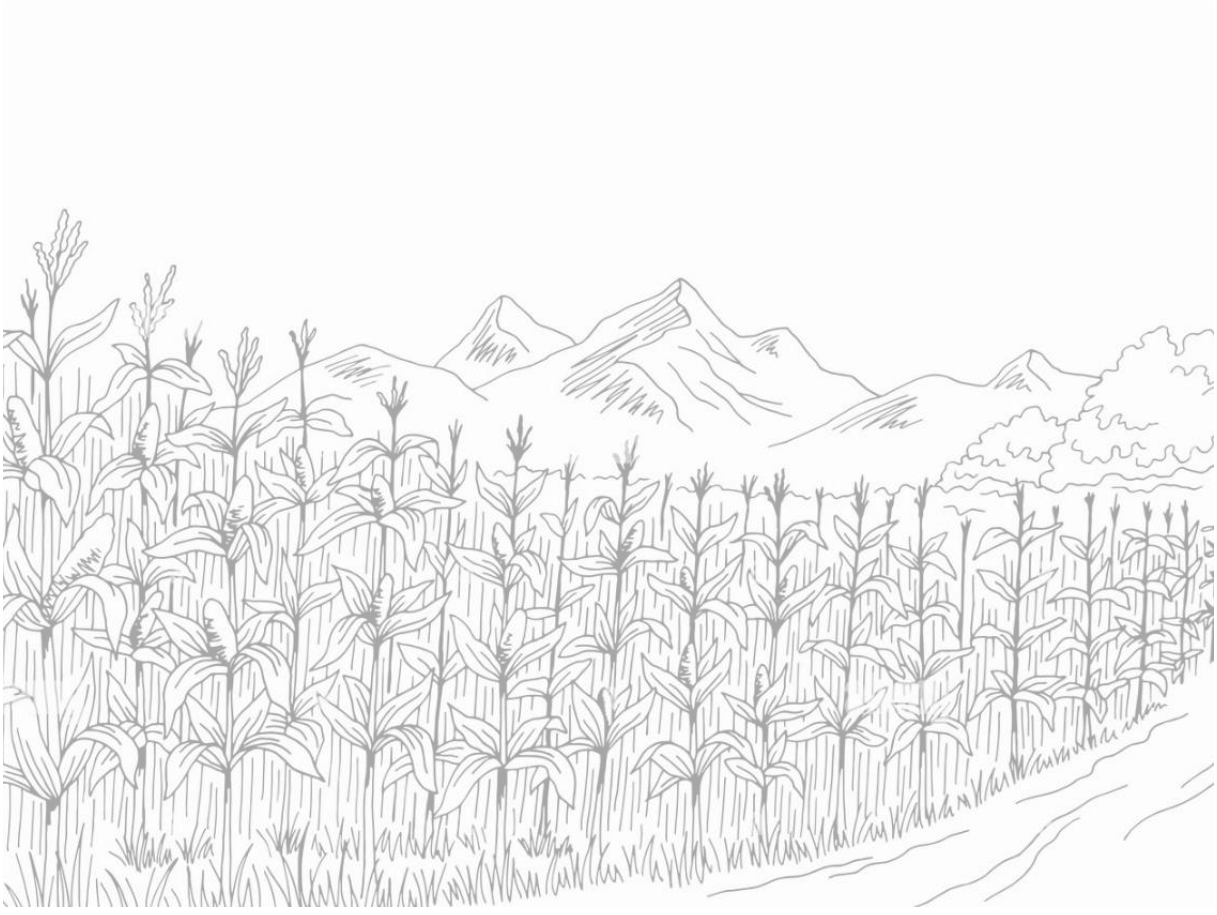
Pourquoi cette thèse ?

J'ai débuté ma carrière professionnelle par des missions d'ingénieur de recherche en agronomie, d'abord à l'INRA au cours de mon stage de fin d'études de l'Ecole d'Ingénieurs de PURPAN puis, entre 2010 et 2016, au sein même de l'Ecole et plus particulièrement sur le Domaine de Lamothe, l'exploitation agricole et expérimentale de l'Ecole. Durant cette période très enrichissante, j'ai eu l'occasion de conduire des projets de recherche dans leur intégralité : depuis la rédaction de réponses à des appels à projets à la valorisation de données via des articles scientifiques ou des présentations lors de conférences. Le travail de terrain occupait également une part significative de mon travail, aussi bien sur des aspects techniques de conduite des cultures que sur la collecte de données scientifiques. J'ai eu la chance durant cette période de pouvoir développer une approche systémique de l'agronomie, en travaillant sur des projets centrés autour de la conception et de l'évaluation multicritères de systèmes de cultures alternatifs à la monoculture de maïs. Cette activité a pu se développer grâce à la mise en place au sein de l'Ecole d'une toute nouvelle plateforme d'expérimentations agronomiques comportant deux blocs de 15 méso-parcelles expérimentales permettant un suivi agronomique et environnemental fin, en particulier concernant la gestion quantitative et qualitative de l'eau.

Malgré l'intérêt porté pour ces missions, mon attrait pour la production a toujours été très fort. J'ai ainsi pris en charge la responsabilité du Domaine de Lamothe (9 salariés, 220 ha, 120 vaches laitières, 6000 poules pondeuses) entre 2016 et 2018. Durant ces deux années, je me suis donc éloigné du monde de la recherche bien que j'aie encadré ma successeure à mon poste précédent d'ingénieur de recherche et aie continué à suivre les travaux et valorisations en cours. Au cours de cette période, j'ai enrichi ma vision et ma connaissance de l'agriculture en étant confronté aux problématiques et aux opportunités technico-économiques du monde agricole. J'ai, au cours de cette période, changé d'échelle de réflexion, en passant du système de culture au système d'exploitation dans l'objectif d'amorcer une transition agroécologique de celui-ci. J'ai ainsi pu appréhender l'imbrication des différentes échelles et de la complexité du pilotage d'une transition durable au sein d'une exploitation.

C'est avec cette vision renouvelée et élargie que j'ai débuté en septembre 2018 ma carrière d'enseignant-chercheur en agronomie. Après une première année de prise en main des différents enseignements d'agronomie et la coordination d'un domaine d'approfondissement en agroécologie, j'ai repris mes activités de recherche autour de la conception et l'évaluation multicritère de systèmes de culture œuvrant pour la transition agroécologique. L'objectif de cette activité de recherche est de continuer à valoriser les données agronomiques et environnementales collectées en continuité sur la plateforme agronomique depuis 2010. Cette reprise d'activité scientifique s'est concrétisée par mon inscription en thèse fin 2019. Ce travail de thèse s'est fait en parallèle de mes activités d'enseignement et de recherche (montage et coordination de réponses à des appels à projet en particulier) et a donc consisté en la compilation des travaux initiés en 2010 et en la valorisation de données environnementales et agronomiques déjà collectées sur le dispositif système de culture de la plateforme agronomique qui possèdent une cohérence thématique avec i) une évaluation multicritère des systèmes de culture, ii) une étude de la gestion des adventices et de l'évolution de la dynamique de la flore adventice en systèmes maïsicoles et iii) l'impact des systèmes de culture et de leurs pratiques de désherbage sur la qualité de l'eau.

Introduction générale



A cropping system is a term that includes the crops that are present in the rotation, their sequence and the technical management applied to these crops and fallow periods (Sebillotte, 1990). Cropping systems including maize (called "corn" in US literature) have been largely studied by the literature in the last thirty years with a total of 25576 publications between 1991 and 2022 (analyse made on the 2022/12/13) (Figure 1). These publications on maize cropping systems concern mostly productivity, despite that topic dropped from 62% of the publications in 1991 to 49% of the publications in 2020. On the contrary, the publications considering the environment raised from 11% in 1991 to 37% in 2020. The publications dealing with cropping systems including maize and both productivity and environmental aspects come mostly from the United-States (36%) and China (23%). Several European countries ranked from third to sixteenth: Germany (6%), Italy (5%), England (4%), France (4%), Netherlands (4%), Spain (3%) and Switzerland (2%). These countries are among the most maize productive regions in the world (see chapter I).

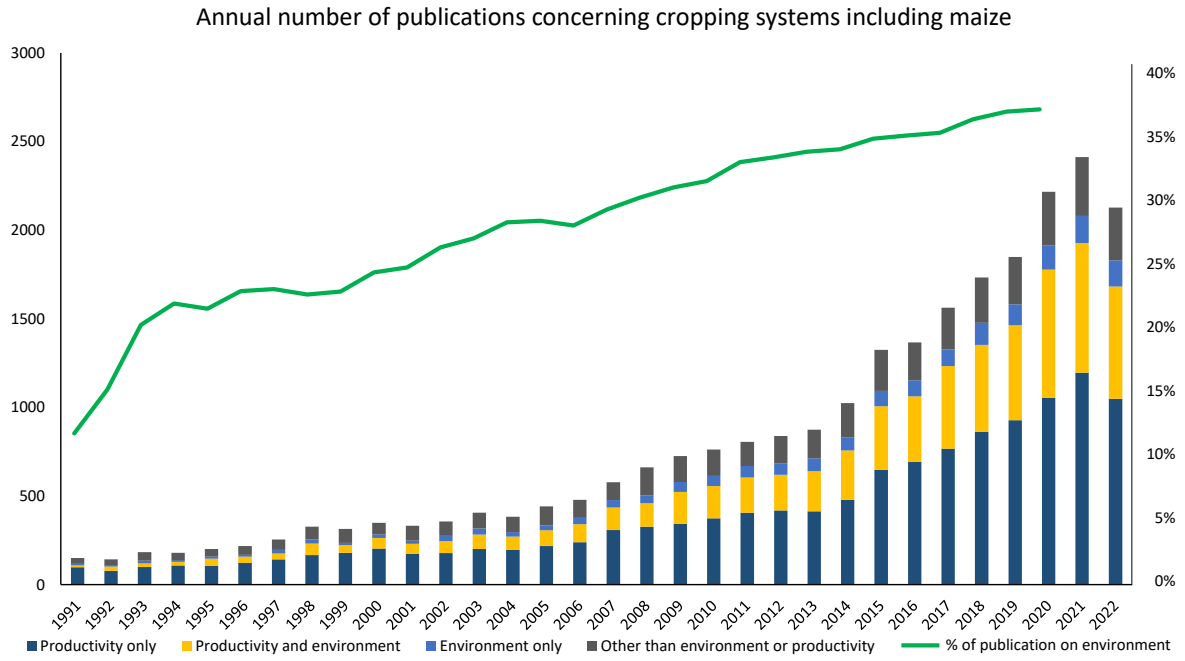


Figure 1: publications on maize-based and corn-based cropping systems (% of publication on environment is a 5-year moving average)

Hereafter, Maize-Based Cropping Systems (MBCS) considered are the ones that include 50% or more of maize in the rotation. On the other hand, the term of conventional MBCS used afterward refers to the dominant MBCS in the regions and countries studied. It is characterized by its short rotation, elite (including GM) varieties and an important use of external inputs (namely fertilizers, fuel, and pesticides), leading to several environmental concerns.

These MBCS are often saw as an archetype of the "industrialized" or "intensive" agriculture, notably because their important use of inputs, in particular pesticides, nitrogen and irrigation water and their consecutive quantitative and qualitative impacts on natural resources (water, soils) and on greenhouse gases emissions. The MBCS are also probably pointed because they often are enclosed in an, as well, "industrial" alimentary system dominated by few multinational companies for the seeds, fertilizers, and pesticides supply but also for the selling and

transformation as a feed, fuel or food. The very little share of maize directly destinated to human food contributes to reinforces the critics made on industrialized MBCS.

That controversy is well present in southwestern France for several years that is one of the main European production region. Maize is one of the most profitable and mastered crops in the region. Indeed, in that region, maize is mainly cropped in monocultures or very short rotations and its management lies in deep tillage that leaves a bare soil for long periods, the use of chemical herbicides to control weeds in the early crop stages, a mineral nitrogen fertilization and irrigation to support crop growth in that temperate climate with low summer precipitations. Because of that management, erosion is increasing and weed resistances started to develop. Moreover, water quality is also strongly impacted because of nitrate and herbicide concentrations. As an example, metolachlor, one of the main maize herbicide, was detected in more than 40% of the water samples in southwestern France (AEAG, 2018). The pollutant concentrations measured do not respect, at the territorial scale, French commitment on nitrate directive (91/676/EC) and on the Water Framework Directive (2000/60/EC). That consistent failure to meet water quality standards with the existing norms generates a legislative reinforcement on the national applications of these European directives and to ancient and probable coming herbicide molecules withdraw (atrazine, glyphosate, S-metolachlor…).



Les opposants aux bassines leur reprochent de favoriser l'irrigation du maïs et la poursuite de pratiques agricoles nuisant à la qualité de l'eau. | OUEST-FRANCE

Figure 2: Illustration of the basin controversy in the regional newspaper "Ouest France" (Bonnardel, 2021). *Legend says: "The basin opponents blame that the basins favour maize irrigation and the continuing of an agricultural management deleterious for water quality".*

MBCS in southwestern France is pointed since several years concerning water quantity management because of a dry summer that questioned the share of water between the different uses and limited water accessibility for many farmers. Water quantity management in conventional MBCS were also present in the media because of a project of basins implantation in the northern part of the region (Figure 2). Indeed, while these basins have the objective to secure the accessibility of water and increase the share of irrigated land in the region, they are criticized by their opponents on the fact that they are implanted mainly to irrigate maize destinated to feed, for animals in majority not bred in the region.

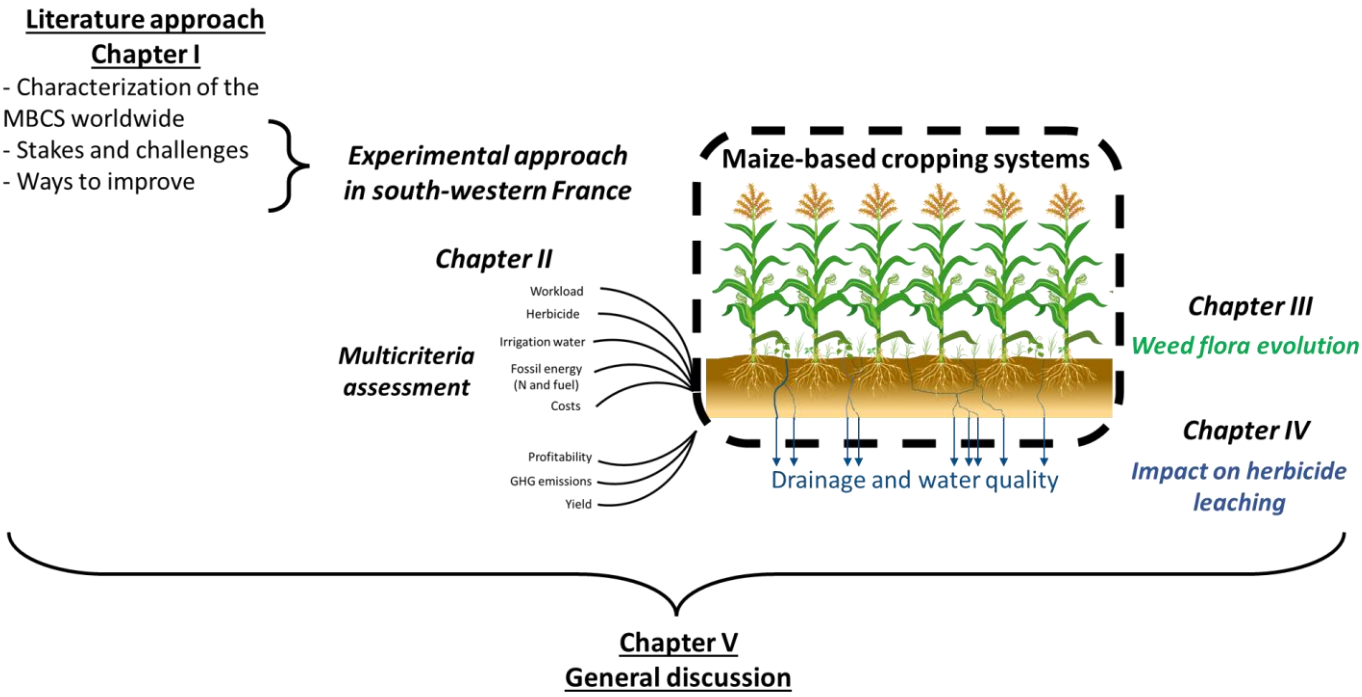
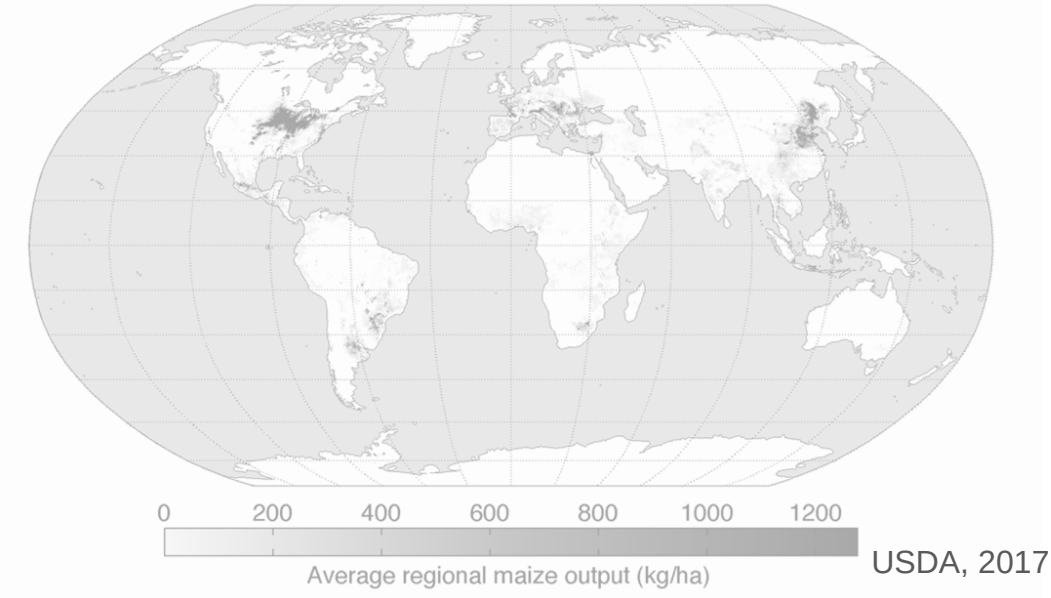


Figure 3: graphical representation of the outline of the thesis

The characterization of maize production and the main conventional MBCS in temperate climates along with the environmental and ecological questions raised by this system is done through a literature review in the first chapter of the thesis (Figure 3). It is followed, in chapter II, by a multicriteria assessment of various experimental low-input maize-based cropping systems in transition towards agroecological management. These MBCS mobilized a systemic approach using several levers such as tillage reduction or diversification. Two sharp points are emphasized by the first two chapters of the thesis: the difficulty to manage weeds in some MBCS and the impact of conventional MBCS on water quality. Therefore, a detailed study on the impact of various experimental MBCS on weed flora dynamics is made in chapter III and a detailed study on the impact of these MBCS on herbicide leaching is the chapter IV topic. The manuscript concludes with a general discussion (chapter V) that draws the conclusions of the thesis and the perspectives for future research in that domain area.

Chapitre I
Revue de littérature des systèmes de culture maïsicoles dans les principaux bassins de production en climat tempéré : caractéristiques techniques, impacts environnementaux et perspectives d'amélioration



USDA, 2017

I. A polarized maize production dedicated to feed and biofuels

1. Production and productivity

In 2019, grain maize was the largest agricultural commodity worldwide with 1150 Mtons produced on 197 Mha. In respect with rice and wheat, the two other main commodities (899 Mtons and 967 Mtons, respectively), maize is a C4-plant and thus benefits of a higher productivity. In 2019, average yields were 5.8 t ha^{-1} for maize, 3.7 t ha^{-1} for wheat and 5.0 t ha^{-1} for rice (FAOSTAT, 2021). Moreover, from 1993 to 2019, maize production increased more than other grain crops in terms of area (+46%, +11% for rice, -1% for wheat), yield (+50%, +26% for rice, +40% for wheat) and total production (+118%, +41% for rice and +39% for wheat) (Erenstein et al., 2022).

Grain maize production is widely distributed around the world with 169 producing countries, which is more than wheat (124 countries) and rice (117 countries) (FAOSTAT, 2021). This shows the adaptability of the maize to various pedoclimates. However, maize production is dominated by few countries/regions in the world. The two main producers, the United States of America and China, represent 30% and 23% of the world production, respectively (Figure I.1). South-America with Brazil and Argentina representing 9% and 5% of the world production, respectively, is another important production region, as is Europe with approximately 10% of the world production (FAOSTAT, 2021). Main African producers are South-Africa, Nigeria and Ethiopia, each representing approximatively 1% of the world production.

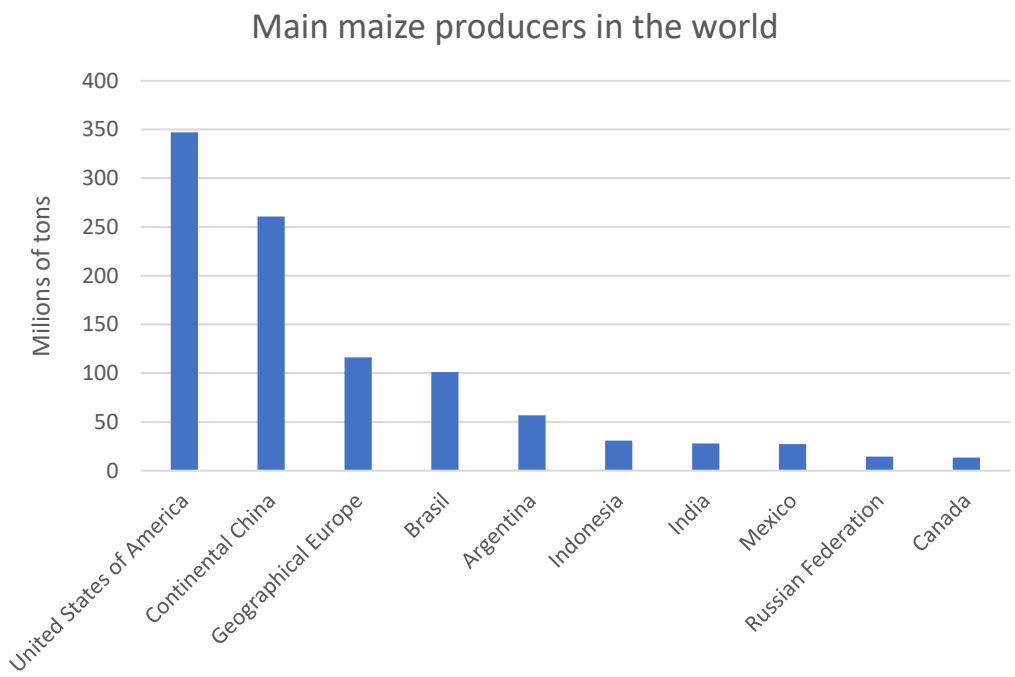


Figure I.1: Main maize producers in the world in 2019 (FAOSTAT, 2021)

There is an important variability in productivity according to the countries with, generally, European and North American countries showing a high productivity (*e.g.* US 10.5 t ha^{-1}, Spain

11.7 t ha^{-1} or Italy, 10.0 t ha^{-1}) while China's yields are moderate (6.3 t ha^{-1}). South-American yields are 7.8 t ha^{-1} in Argentina and 5.7 t ha^{-1} in Brasil. However, African yields are much lower: 4.9 t ha^{-1} in South-Africa, 4.2 t ha^{-1} in Ethiopia and down to 1.6 t ha^{-1} in Nigeria (FAOSTAT, 2021). Production is limited in Africa (2.1 t ha^{-1} in average for the whole continent), mainly because of water stress (Erenstein et al., 2022).

In the present study, a particular focus will be made to the biggest productivity areas in temperate climates. Indeed, some of the most productive agroecosystems are also among the worst in terms of negative externalities and environment impact because of intensive use of external inputs including pesticides and fertilizers (German et al., 2017). Matson et al. (1997) listed the main factors that leaded to the losses of ecosystem properties with the adoption of industrial agriculture: monocultures with low genetic diversity and the consecutive use of pesticides, intensive tillage, overuse of N and P fertilizers and irrigation. These factors are particularly present in the temperate MBCS (mainly North America, Europe and China) on which the present study will focus.

a) A wide range of climate available, broadened with irrigation

Maize shows an important flexibility in terms of climate requirements (Figure I.2). Ramirez-Cabral et al. (2017) showed the main unsuitable zones for maize production are deserts (*e.g.* Sahara, Central Australia), mountains and other cold places (*e.g.* Himalaya, Siberia, Groenland). Indeed, these areas correspond to the areas where lethal stresses are observed: cold stress with below 0°C temperatures during the maize cropping season (*e.g.* Siberia), heat with temperatures above 46°C that kill maize (*e.g.* Sahara region, central Australia), dry stress (*e.g.* South America, especially in the northern part of the Andes mountains) and wet stress because of waterlogging (*e.g.* Indonesia) (Ramirez-Cabral et al., 2017).

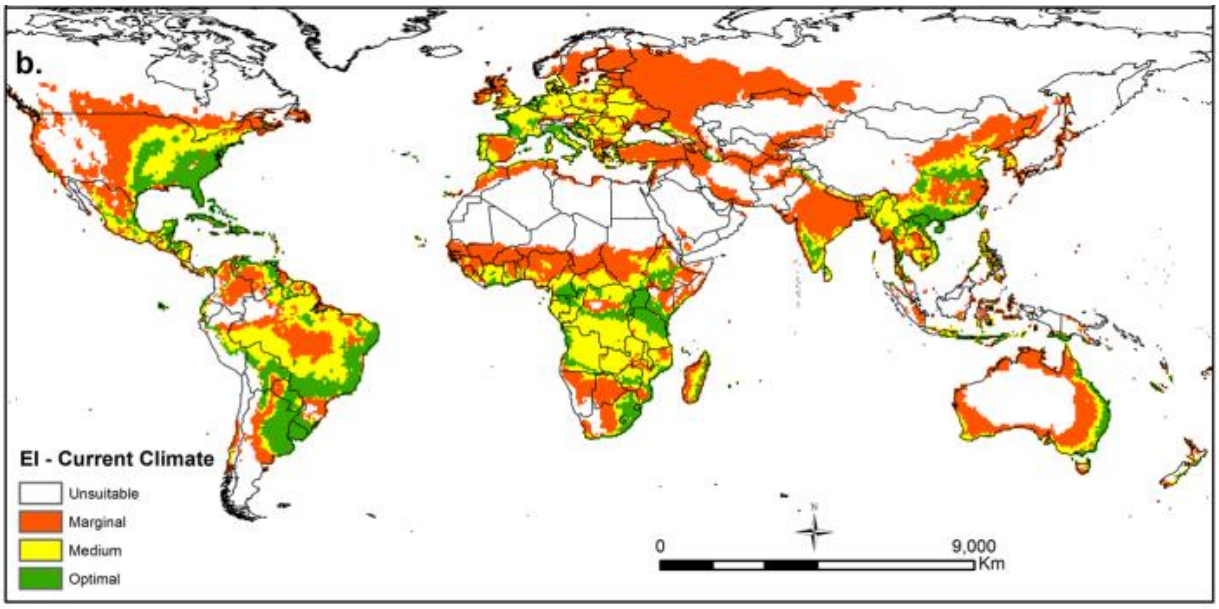


Figure I.2: Ecoclimatic Index of maize (Ramirez-Cabral et al., 2017)

The authors identified that water stresses are one of the main threats for maize cropping, that should amplify in next years. While cold and heat stresses cannot be managed by reasonable management techniques at a farm scale, drainage was developed in some regions to limit waterlogging and irrigation to avoid drought stress. Drought stress is by far the constraint that

has been the most prevented in maize production, by developing drought tolerant varieties and irrigation: 18% of the entire cultivated land in the world is irrigated and maize is among the main irrigated crops in the world ("WAD | World Atlas of Desertification," n.d.).

Irrigation varies according to the region. While irrigation is used on only 4.3% of the maize acreage in Brazil (Flach et al., 2020), it represents approximatively 36% of the acreage in the US ("USDA ERS - Feedgrains Sector at a Glance," n.d.) and 46% in China (Zheng et al., 2020). In Europe, maize irrigation is important, but the proportion of irrigated maize is highly variable according to the regions. It is widely used in southern regions such as Spain, Portugal, Italy, Greece or France: more than 80% of maize is irrigated in the Po valley, northern Italy (Vasileiadis et al., 2011) and 50% in South-western France (Agreste Nouvelle Aquitaine, 2018). Northern European countries (Denmark, Germany or the Netherlands) also have little acreage of irrigated maize (Zajac et al., 2022). However, in those countries, the amount of water used per hectare is much lower, with only one or two irrigations around maize flowering (Vasileiadis et al., 2011).

Access to irrigation often influences the farm structure, as labour requirements can be high in the case of surface irrigation systems and irrigation with pressured water (through sprinkler, central pivot or hose reel) is capital intensive. On irrigated arable farms, crop production pays off the investment in irrigation system and/or the workforce dedicated to irrigation. In many cases, rotations are shortened to increase irrigated maize acreage. The level of irrigation in maize production is very variable across the regions. It can be only 30 mm ha^{-1} in Denmark (Vasileiadis et al., 2011) while, in the North-China Plain, the dry climate imposes an important irrigation with an average of 300 mm ha^{-1} and maximum up to 670 mm ha^{-1} (Tan et al., 2017). Globally, maize yield increase due to irrigation is estimated at 22±13%. The variability of the yield increase is high because maize irrigation is implemented in very contrasted climates, especially in terms of precipitations amount (*e.g.* Denmark vs South of Spain) (X. Wang et al., 2021). Moreover, the development of irrigation may have consequences for other uses and natural ecosystems (X. Wang et al., 2021).

b) Grain maize uses

At the world scale, maize production is valorised at 13% for human consumption, 56% for animal production and 20% for non-food uses, mainly biofuels. However, maize use varies drastically by regions. In many developing countries of Sub-Saharian Africa or Latin America, maize is mainly cropped for direct human consumption, by farmers with land scarcity that take advantage of a high productivity of maize. In eastern and southern Africa, maize is used at 66% for food and represents 24% and 22% of the calories and proteins consumed by people, respectively (Erenstein et al., 2022). However, in the United States, seed production, starch industry and direct human consumption represent together less than 10% of the total maize consumption (Shiferaw et al., 2011; "USDA ERS - Feedgrains Sector at a Glance," n.d.).

The destination of maize for feed has increased in last 60 years with the increase of the meat consumption, especially in Europe, Asia and America (Erenstein et al., 2022). In the most developed countries, the use of grain maize for feed is dominant and reinforced if one includes also the surfaces cultivated for silage use. In China, 67% of grain maize is used for animal consumption (Li, 2009). However, the use of maize in the last past years increased the most for energy production (Ranum et al., 2014) such as biogas in Germany (von Redwitz and Gerowitt, 2018) and bioethanol. In the United States, bioethanol production represented approximately

50% of the production at the end of 2010's years ("USDA ERS - Feedgrains Sector at a Glance," n.d.).

Present document focused on the moderate to high yields MBCS in temperate climates, mainly dedicated to feed and biofuels and that rely on irrigation for their productivity. These cropping systems are mainly located in the United States, China and Europe that are taken as examples of contrasted and emblematic MBCS: similarities and differences are emphasized in the next part.

2. *Well-established intensive maize-based cropping systems in temperate climates*

a) United-States

Cropping sequences

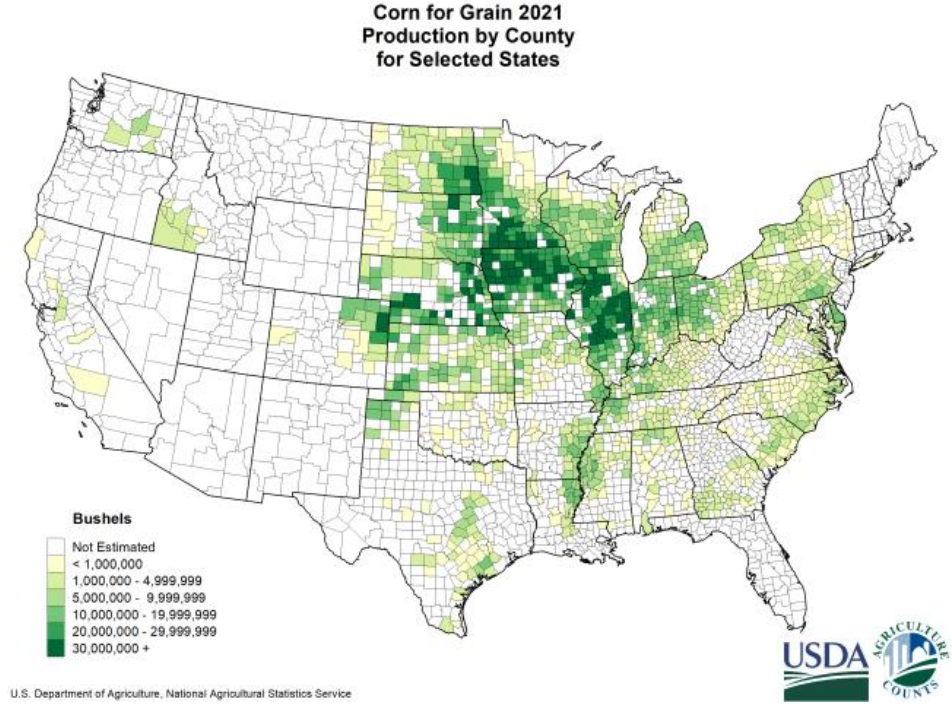


Figure I.3: Map of maize production distribution in the United-States (USDA, 2022)

The United States of America is the top grain maize producer in the world and production has continued to increase in the last several years (Saavoss et al., 2021). Corn farms in the United States are usually large, almost 300 ha (Saavoss et al., 2021). The US Corn Belt is a north-central region including notably North and South Dakota, Nebraska, Minnesota, Iowa and Kansas represents 90% of the national production (Figure I.3, Grassini and Cassman, 2012; Tenorio et al., 2020). In the Corn Belt, maize is often cultivated in continuous cropping or in maize-soybean 2-year crop rotation without cover crops during winter. These crop sequences tend to increase at the expense of wheat, oat, dry beans and grasslands that were cultivated marginal land susceptible to erosion risks and close to wetland areas (Gaudin et al., 2015; Wright and Wimberly, 2013). In the Corn Belt, the share of maize cropped continuously or after soybean represents more than 85% of the maize. On that area, soybean-maize rotations are

dominant (65%) in respect with continuous maize (35%) (Farmaha et al., 2016; Tenorio et al., 2020).

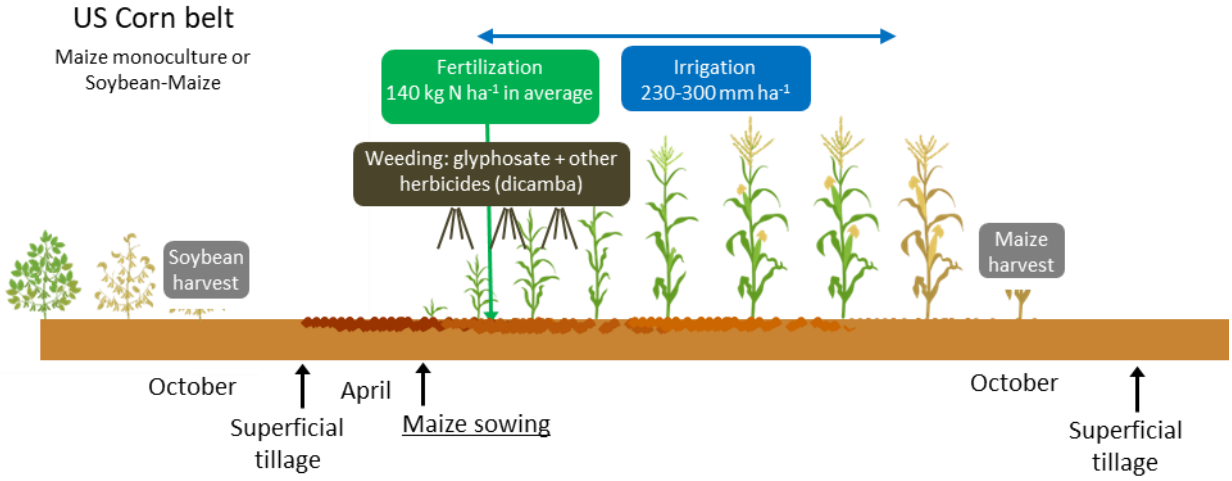


Figure I.4: Technical management of Maize in MBCS in US Corn belt

Tillage

Conventional tillage represented only 32.6% of maize acreage in 2016. Use of conventional tillage reduced over the last several years (38.5% in 2005) because of an increase in conservation tillage (no tillage and mulch tillage) that permitted to significantly reduce soil erosion (Claassen et al., 2018).

Pest management

In 2018, GM-maize accounted for 92% of the US maize acreage. Almost 80% of the acreage was constituted of stacked GM-maize, combining the glyphosate tolerance and the insect resistance ("USDA ERS - Charts of Note," n.d.). Most of pest management relies thus on genetic engineering and pesticide use (Figure I.4). If GM-varieties allowed to reduce the use of insecticides from 0.31 treatment year^{-1} in 1996 to 0.13 in 2010 (Saavoss et al., 2021), it was not the case for herbicide since 77% of the maize cropped in the US in 2014 was treated with glyphosate while only 4% was concerned in 1996. In average, weed control was performed through 3.6 treatments in 2016 while it was 2.5 in 1996 (Saavoss et al., 2021). As the number of cases reported glyphosate-resistant weeds increased during the last years, glyphosate dose increased at 0.39 kg of active ingredient (+23% between 1996 and 2014) and frequency of application increased at 1.19 applications per year, +19% between 1996 and 2014 (Benbrook, 2016). Weeding also continued to rely on atrazine that was applied on 55% of the maize acreage (Benbrook, 2016). Maize protection against pests is completed with seeds coated with neonicotinoids such as imidacloprid for almost all the maize acreage (Tooker et al., 2022).

Irrigation

Irrigation is present for maize production in the US, with an increasing importance from East to Center United States (X. Wang et al., 2021). Irrigation rate is highly variable according to the annual climate and precipitations. In a regional study between 2005 and 2007, Grassini et al. (2011) estimated that the average irrigation rate was 229 mm ha^{-1} in the fields equipped with central pivots and 388 mm ha^{-1} for surface irrigation, the two main irrigation systems present in the region. 300 mm ha^{-1} is an average of maize irrigation in the High Plains (Smidt et al., 2016). Globally at the US scale, irrigation is declining and is only present on 11% of the maize acreage in 2016, especially because of the cost increase due to an important reduction of the groundwater availability (Saavoss et al., 2021). At the same time, pressurized systems – that allow a better water management – are getting predominant in the Corn Belt.

Mineral fertilizers

N-balance in maize cropped in the Corn Belt tends to be high. Tenorio et al. (2020) revealed in their study that in irrigated MBCS of two regions located in the Corn Belt that N-balance was above 77 kg/ha. Mineral nitrogen was applied at 140 kg ha^{-1} in average at the US scale in 2016, in a steady increase (Saavoss et al., 2021). In average, 30% of the US Corn Belt maize fields are N fertilized in autumn which can cause environmental problems linked with N dissipation in the environment (Millar et al., 2010; Ransom et al., 2020). On the contrary, the frequency and dose of phosphorus and potassium applications decreased since 1996.

b) China



Figure I.5: The Chinese Corn Belt (Hu and Zimmer, 2013)

Cropping sequences

Chinese maize production is characterized by very small farms, averaging less than 1 ha to 2.2 ha according to the provinces (Li, 2009). However, because of the small size of the farms, several neighbouring farms are often cropped together (Hu and Zimmer, 2013). North China Plain (provinces of Hebei, Shandong, Shanxi and Henan) is the main grain maize production region in the country with 35% of the national area (Ren et al., 2021). The provinces of the Chinese Corn Belt, numbered from 1 to 11 on figure I.5 account for 83% of the Chinese maize production (Hu and Zimmer, 2013). Three dominant MBCS are present in the Chinese Corn Belt. In its northern part, the dominant MBCS are continuous maize cropping or a maize-soybean two-year rotation. In the central part of the region, the rotation includes a maize sown as a double crop after wheat and this is often done year after year (Ren et al., 2021; Xiao et al., 2019). Finally, in the south part of the Chinese Corn Belt, a mountainous area, maize is cropped once or twice a year in triple cropping annual rotation. Double and triple cropping systems are expected to increase in the next years because of global warming (Zhao and Guo, 2013). In

China, maize is also interplanted or rotated with potatoes, cotton, rice or wheat. High yields are possible because of improvement due to maize cultivars and an optimized plant population. However, that high yield potential (11.64 t ha^{-1}) is not reached (from 4.0 to 8.4 t ha^{-1} in average for the best provinces) especially because of a too low planting rate, not adapted to the pedoclimatic conditions (Hu and Zimmer, 2013; Ren et al., 2021).

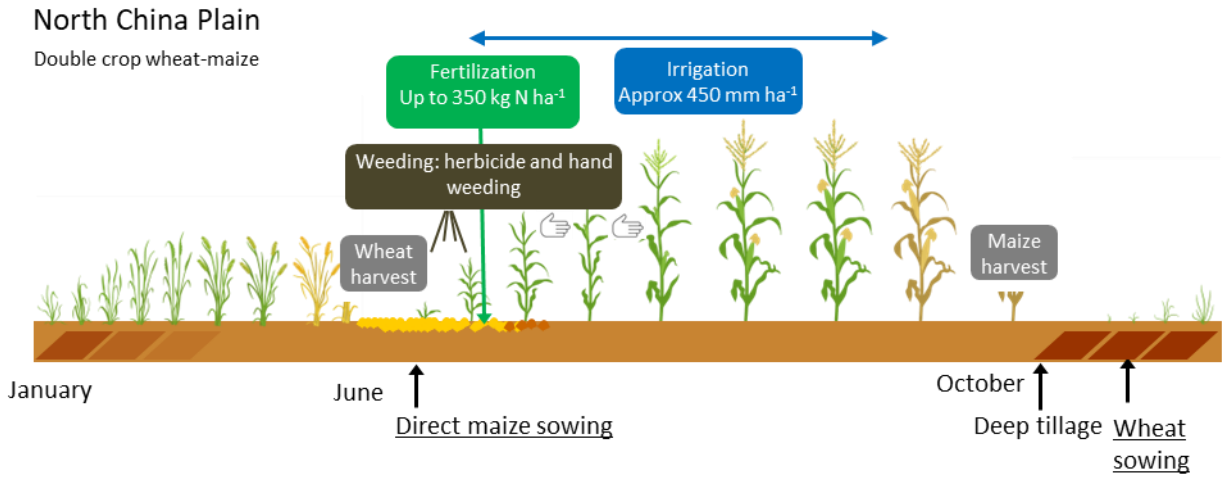


Figure I.6: Technical management of maize in double cropping system in North China Plain

Tillage

When maize is the unique crop of the year, tillage can occur twice: before winter then in spring just before sowing (Meng et al., 2006). It is deep tilled once a year in the wheat-maize double cropping system, usually before wheat (Figure I.6). Where the growing season duration is short, maize can be sown without tillage directly into the wheat as a relay-crop. However, the practice of fall tillage is decreasing, mainly because off-farm employment reduces the available time for cropping. In the colder locations, tillage is done to increase soil temperature, limit weeds and pests but also to increase soil temperature and to lengthen crop cycle (Meng et al., 2006).

Pest management

While weeds remain largely managed by hand or by hoeing, herbicide use is increasing a lot in China despite little data is available on that topic. If insecticides were the first adopted chemicals to fight especially against Asian corn borer, herbicides are now representing the main pesticide use in China due to the adoption of *Bt* maize and to the reduced agricultural workforce available in the country. In 2007, it was estimated that 44% of the maize areas in China were sprayed with herbicides (Gianessi and Williams, 2011). The use of herbicides is more common on irrigated land in North China Plain that adopted a more intensive management. The most common herbicides used on maize in China are 2,4-D, atrazine, metolachlor and glyphosate… 2,4-D and atrazine and related compounds were found at very high concentrations in river and groundwater (0.96 to 9.7 µg L^{-1}), which reinforces the perception that herbicide overuse is common (Brauns et al., 2018). In some regions, seeding is done in conjunction with applying plastic mulch, used mainly to improve soil warming in the coldest locations but also useful to manage weeds on and around the row crop (Meng et al., 2006).

Irrigation

Rainfed maize represents 55% of maize production in China (Meng et al., 2006). Irrigated land is mainly present in the northern part of the Corn Belt but maize is often not the most irrigated

crop since a priority is given to wheat (Brauns et al., 2018; Meng et al., 2006). However, irrigation is important in the case of summer maize of North China Plain, irrigated in 80% of the cases with recommendations at 450 mm ha^{-1} (T. Zhang et al., 2021) and important rates up to 670 mm ha^{-1} (Meng et al., 2006; Tan et al., 2017). The dominant irrigation system in China is flood irrigation, known for its low water use efficiency (T. Zhang et al., 2021).

Fertilization

The use of inputs is rather important on Chinese maize. Despite maize cultivation being heterogeneous between provinces, it is often conducted with high mineral fertilization rates: 550-600 kg N ha^{-1} is quite typical in the North China Plain despite it can be lower, situated between 225 and 350 kg N ha^{-1} for other farmers (Ju and Zhang, 2017; Ju et al., 2009; Ren et al., 2021). In the high-yielding zones, up to 774 kg N ha^{-1} can be spread on maize (Chen et al., 2011). The use of mineral nitrogen is increasing while organic manure is decreasing (Ju et al., 2009; Meng et al., 2006). Fertilization is often applied in only one time (Ren et al., 2021). The inputs are not always optimized (excessive mineral N, optimum would be 203 kgN/ha) and planting rates are too low. On an annual study, Brauns et al. (2016) identified that on an entire year of double crop wheat-maize, 408 kg N ha^{-1} were spread (149 kg N ha^{-1} on maize) but was in excess by approximately 320 kg N ha^{-1}. Ju et al. (2009), on a regional study, estimated that the common excess of nitrogen supply (mineral and organic) was 212 kg N ha^{-1} on double crop wheat-maize cropping systems, while it was estimated at 457 kg N ha^{-1} in the high yielding zones by (Chen et al., 2011).

c) Europe

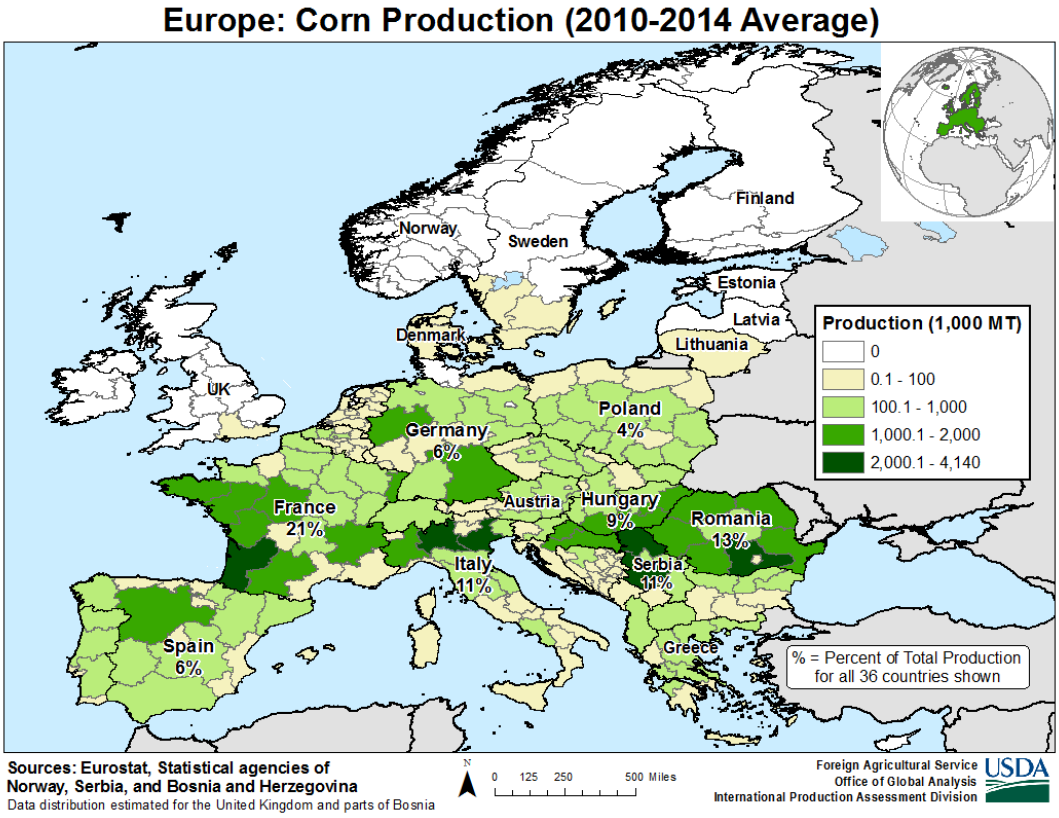


Figure I.7: Map of maize production distribution in Europe (2010-2014 average) (USDA, 2015)

Cropping sequences

Grain maize is mainly produced in central and southern Europe while silage maize is mainly produced in northern Europe (Figure I.7, Vasileiadis et al., 2011). The majority of European maize is produced in rotation with other crops but continuous maize cropping is also common in some regions. For example, continuous maize cropping represents 50% of the maize cropped in Tolna region in Hungary, 30% in the Po plain of Italy, one of the largest European maize areas (Bussay et al., 2015; Vasileiadis et al., 2011). In France, continuous maize cropping represents around 20% of the maize area, but that sequence is more present in the south-west of the country, where it can represent up to 80% of the areas (Meissle et al., 2010; Mercier-Poirier, 2014).

In almost all the European countries, maize is essentially rotated with winter cereals and in particular winter wheat. Longer rotations are scarcer but often include soybean, grass or oil seed crops (Mercier-Poirier, 2014; Vasileiadis et al., 2011). Maize monoculture or short rotations increase in some European regions because of the new uses of the crop (*e.g.* Germany for biogas) (von Redwitz and Gerowitt, 2018).

While rainfed maize reaches yields between 2.9 and 11.8 t ha^{-1}, they average around 10 t ha^{-1} for irrigated maize except for Albania and Portugal where they are at 6 t ha^{-1}. At the European scale, there is a global West-East gradient with eastern Europe having more reduced yield than western Europe, a region having relatively low yield gap because of an intensive use of inputs (Schils et al., 2018).

The size of the farms that grow important acreage of maize is intermediate between US and China model. Maize farms are on average at 16 ha in southern Europe (Masseroni et al., 2017), in France maize is cultivated on approximately 18 ha on a total cropped area of 69 ha in south-western France, where most of grain maize is produced in the country (Agreste Nouvelle

Aquitaine, 2021, 2018). In Eastern countries as in Romania, farm structures are very heterogeneous with 91.8% of very small farms (<5ha) and 0.5% of larger farms (>50 ha). These larger farms crop more than 50% of the land (Eurostat, 2018).

Tillage

Ploughing remains the main common tillage practice before maize in Europe (Meissle et al., 2010; Mercier-Poirier, 2014). Ploughing facilitates soil warming in spring and thus enhances maize germination and helps to control pests as European corn borer, annual weeds and diseases, especially *Fusarium sp.* (Meissle et al., 2010). Non-inversion tillage represents only 22% of the maize cropped in France, a valid magnitude all across Europe (Agreste, 2020; Meissle et al., 2010).

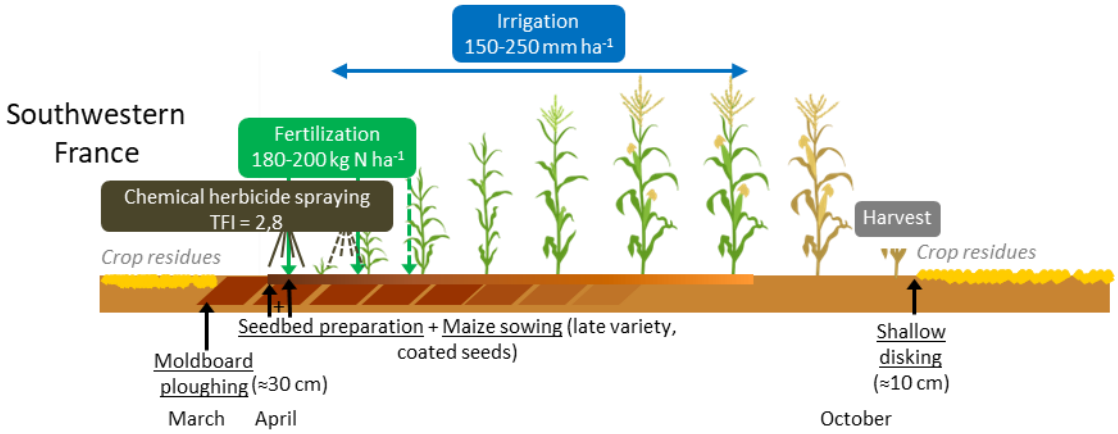


Figure I.8: Technical management of maize in continuous cropping system in Southwestern France

Pest management

Integrated Pest Management (IPM) methods are poorly adopted by European farmers, despite strong differences between regions (Meissle et al., 2010; Vasileiadis et al., 2011). Based on farmers declarations, IPM was practised by 5 % to 100 % of the farmers. However, the most common point among regions was the reliance on pesticides with herbicides being the most applied category of pesticide (Vasileiadis et al., 2011). More than 90% of European maize areas are sprayed with herbicide, 98% in France (Agreste, 2020; Meissle et al., 2010) with strategies varying between pre-emergence and post-emergence application, depending on the molecules used and the weed flora present in the field. Even if atrazine is forbidden in Europe since 2004, organochlorine, sulfonylureas, triketones and benzoylcyclohexanedione herbicides are commonly used (Bibard, 2014; Meissle et al., 2010).

Differently from US and China, Europe did not – or marginally – adopt GM-maize so pest control, mainly against European and Mediterranean corn borer, essentially relies on cultural control and on application of insecticides, including seed coating (Meissle et al., 2010; Vasileiadis et al., 2011). Cultural control is made through tillage and in particular ploughing and false seedbed techniques to manage weeds (Vasileiadis et al., 2011). GM prohibition also promoted the development of biocontrol with Trichogramma (*Trichogramma* sp.) to manage European corn borer. It is developed on approximately 150 000 ha in France (10% of the national acreage) (Contrat de solutions, 2022). However, almost all European surface is treated with fungicides and insecticides, mainly by seed coating or applications at sowing (Meissle et al., 2010).

The total Treatment Frequency Index (TFI) of grain maize in France is 2.8 (Figure I.8; Agreste, 2020) while it varies from 1.4 to 1.7 in Germany, for continuous maize or rotated maize,

respectively (Andert et al., 2016). According to Meissle et al. (2010) and Vasileiadis et al. (2011), it can be estimated that 1.4 to 2.8 is the good magnitude of the European use of pesticide on grain maize, even if that TFI could be higher on southern regions where corn borer and gramineous weeds can be found in higher populations than in northern regions.

Irrigation

The proportion of irrigated maize varies according to the country considered, especially because of the gain it provides depends on the location (Figure I.9). Irrigation is absent or nearly absent in central-eastern Europe (Romania, Hungary, Germany, Austria, Poland…) and dominant in southern Europe (Portugal, Spain and Italy). France is intermediate with approximately 25% of the maize irrigated at the national scale, but that rate goes up to 50% in southwestern of France with an irrigation level varying between 150 and 250 mm ha^{-1} according to the years in that region (Agreste Nouvelle Aquitaine, 2018; Webber et al., 2018).
Irrigation systems vary between countries: pressure irrigation is dominant in France but gravity-fed irrigation systems are largely (more than 50%) developed in Italy, Spain and Portugal (Masseroni et al., 2017). Gravity-fed system contributes to have reduced field areas of less than 5 ha.

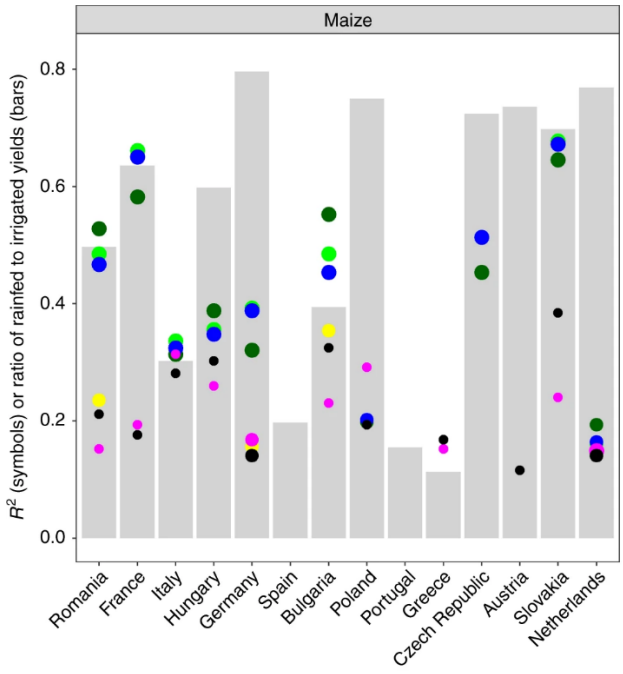


Figure I.9: Proportion of rainfed to irrigated maize yields in several European countries (grey bars) (Webber et al., 2018)

Fertilization

Meissle et al. (2010) and Schils et al. (2018) reported that average N supply on European maize production varied from 100 to 350 kg N ha^{-1} but was around 180 to 200 kg N ha^{-1} in the main productive and irrigated regions (North-Italy and France). In France, grain maize receives 143 kg N ha^{-1} of mineral nitrogen and approximately 50 kg N ha^{-1} of organic nitrogen on average. Maize is one of the crops the more heavily N fertilized in the country, along with durum wheat, oilseed rape, and potatoes. With 22.5 kg P ha^{-1}, maize is also one of the crop that receives the mosre P, along with potatoes and sugar beet but much more than other cereals (Agreste, 2020).

Country (region)	US corn belt	China (Yellow-Huai region)	Europe (South-western France)
Yield (t ha^{-1})	> 10	> 6	> 10
Rotation duration (years)	1-2	1 (or 2)	1 (or 2)
Crops rotated with maize	soybean	wheat, vegetables, sometimes intercropped	soft wheat, soybean
Tillage	Reduced tillage in majority (70%)	Annual tillage	Ploughing in majority
Irrigated area	11% of the area is irrigated in the US, more important in central US	Mainly irrigated	> 50% of the maize area
Irrigation dose (mm ha^{-1})	from 200 to 300	>450	from 150 to 250
N fertilization (kg N ha^{-1})	140-150	150-350+ often one application	180-200
Varieties	Hybrid – GM varieties	Hybrid, occurrence of GM-maize increases	Hybrid, no GM varieties
Pest management	Neonicotinoids at sowing (coated seeds), GM crops	Some insecticides applications	Coated seeds, + insecticide applications in some regions against corn borer
Weeding	Chemical, mostly glyphosate	Chemical, mechanical and by hand	Chemical
Soil management in winter	Mainly bare soil	Frequently cropped with wheat or garlic crops	Mainly bare soil

Table I.1: Main management strategies in an emblematic location of the three regions studied

Conventional MBCS in US, China and Europe can be characterized by the fact that they achieve, most of the time, 75% or more of the yield potential, attaining of the time from 6 to more than 10 t ha^{-1} (Mueller et al., 2012) despite they are in different trajectories in term of use of input and yield evolution, as shown for N by Lassaletta et al. (2014). MBCS are characterized by continuous maize cropping or short and simple 2-year rotations.

Concerning the annual technical management, conventional irrigated MBCS indicates: a heavy fertilization (>150 kg N ha^{-1}, >15 kg P ha^{-1}), an important irrigation (often < 150 mm per year), a deep tillage (mainly ploughed – except in the US) and a long fallow period with bare soil (except in the wheat-maize cropping system in North-China plains). The irrigated regions are characterized by higher productivity and higher use of inputs. The technical management relies mostly on chemicals (except in China where hand weeding can still be found) and GM varieties (except in Europe, despite breeding has been an important driver there too), inducing that they are only slightly affected by diseases and pests.

II. MBCS stakes

1. Profitability

MBCS are among the most profitable grain cropping systems in the regions where they are cropped. Maize productivity per hectare is high, such as in south-western France where maize yields are twice the wheat yield. On the other hand, maize price is only 10 to 20% lower than wheat price (DLG, 2021) while operating expenses, excluding irrigation, are similar (CA Landes, 2022). Langemeier et al. (2020) showed that a conventional MBCS in US as an average net return of 284 \$ ha^{-1}, a level similar to an older study of Koger and Reddy (2005) that reported net returns comprised between 102 \$ ha^{-1} and 352 \$ ha^{-1}. In China, the study by Zhou et al. (2019) revealed net returns ranging from 9062 \$ ha^{-1} to 12742 \$ ha^{-1} according to the crop management applied which is very elevated than another Chinese study (Li et al., 2021) with various tillage and residue management that revealed net returns around 2900 to 3200 \$ ha^{-1}. High positive returns are also recorded in Europe with an average gross margin of 691 € ha^{-1} on 46 years of experiment in Italy (Basso et al., 2011) or 936 € ha^{-1} for southwestern France farms in average from 2017 to 2021. In the same location, during the same period, the gross margin of soft wheat was only 275 € ha^{-1} (CA Landes, 2022).

The alternative management evaluated to improve the environmental performances of MBCS (soil erosion, nitrate leaching…) such as optimized fertilization, reduced tillage or cover crop sowing can either improve or reduce the net return of the MBCS. Optimized fertilization techniques or Decision Support Systems to manage fertilization are more likely to be beneficial (*e.g.* Link et al., 2006; Memic et al., 2019; Zhou et al., 2019) since reduction of cost is one of the reasons why this optimization is applied (Archer et al., 2002) but it also depends from the initial fertilization level. Concerning tillage studies, net return is very sensitive to the yield obtained under reduced tillage. Evaluated at the cropping system scale on the short term, adoption of cover crop is more likely detrimental for net return (Koger and Reddy, 2005; Thompson et al., 2020).

2. Price volatility

As other grain cropping systems, MBCS are highly susceptible to price volatility. First, maize growers are very dependent of that crop economically. Indeed, MBCS can be based only on maize in the case of monocropping or on very few other agricultural commodities (soybean, wheat, or rice) that follow a similar pattern of price evolution (Figure I.10). The market of commodity grains is very variable from one year to another, especially because of the globalisation and the financialization of the market with speculations made on commodities (Awaworyi-Churchill et al., 2022). Recent events, including Ukrainian war and SARS-Cov2, skyrocketed prices and again enhanced price variability (Monge and Lazcano, 2022).

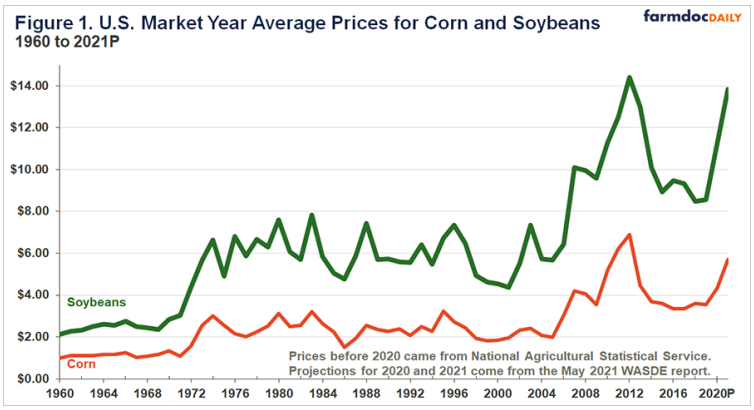


Figure I.10: Evolution of price of maize and soybean in US from 1960 to 2021 (Schnitkey et al., 2021b)

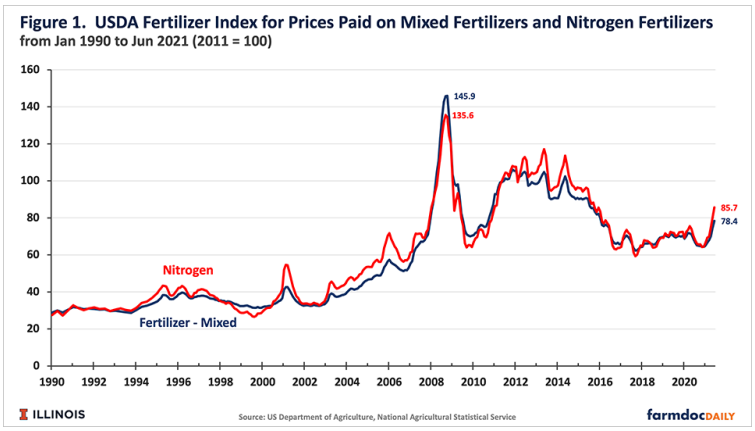


Figure I.11: Evolution of price of maize and soybean in US from 1990 to 2021 (Schnitkey et al., 2021a)

Furthermore, MBCS use important amounts of pesticides and fertilizers (mostly nitrogen and phosphorus). These inputs are also subject to a global price increase: +149% for fertilizer and +20% for chemicals between 1996 and 2016 (Figure I.11, Saavoss et al., 2021) and to an important price volatility. Since nitrogen fertilizer synthesis consumes a lot of energy, the cost of nitrogen fertilizers often follows – or even surpasses – the oil market. That volatility, hard to anticipate, can reduce maize profitability.

3. Resources depletion: quantity and quality

a) Irrigation water

Irrigation is a key factor of maize production and productivity in many regions of the world and that practice is developing worldwide. Many key maize breadbaskets worldwide are irrigated such as North China Plain or the High Plains in the US, where irrigation can double maize yield (Dalin et al., 2017; Smidt et al., 2016). All the more climate change will increase frequency and length of drought periods, hence increasing irrigation needs in the coming years (Challinor et al., 2014).

Many regions use groundwater to irrigate maize at rates that deplete aquifers. For example, the water volume of the aquifer of the South High Plains (US) has been halved between 1950 and 2010 (Smidt et al., 2016). As the aquifer is depleted, the energy needed to pump water increases:

it almost tripled in the North China Plain from 1986 to 2015 up to a level of 1122.4 kWh ha^{-1} (Chen et al., 2019), which impacts negatively the energy balance of maize cropping. Great progress was made to improve water efficiency and reduce energy consumption of irrigation systems with the introduction of precision irrigation and low-pressure devices (T. Zhang et al., 2021). The use of soil tensiometers that follow the amount of available water for the crop can also help reduce irrigation applications but not systematically. These systems are adopted by farmers. However, they resulted in increasing the share of irrigated crops and the watershed depletion continues with the same dynamic (Linstead, 2018; Smidt et al., 2016).

When irrigation uses surface water, it causes water quantity issues both at the farm and territory scale. In a study made in the Mississippi basin, Yasarer et al. (2020) showed that all the tributaries studied indicated a significant flow reduction in the last 30 years and also an important increase of zero flow days, which is dramatic for the river ecosystems. In the mid-term, water withdrawals with a total impossibility to irrigate will increase by 10% in next years, especially in southern Europe because of climate change (Masseroni et al., 2017).

b) Phosphorus

Grain maize contains in average 2.6 g of phosphorus (P) (6 g of P_2O_5) per kilogram of grain (Setiyono et al., 2010). Until maize reaches 60 to 70% of the environment potential, it requires 2.3 g P kg^{-1}. Above 70% of environmental potential, efficiency in P uptake decreases up until the maximum environmental potential, determined by temperatures and solar radiation (Setiyono et al., 2010). Average yields in US, China or Europe exports from 14 to 31 kg P ha^{-1}, which is more than the majority of other row crops because of the high maize yield (COMIFER, 2019).

Actually, phosphorus supply for crops in general and maize in particular is provided at 85% by phosphate rocks. High challenges exist on phosphorus worldwide, since phosphorus is an extracted resource not renewable, unequally distributed worldwide and poorly recycled (Cordell et al., 2009; Reijnders, 2014). Phosphorus creates environmental problems where it has been used in excess: runoff from heavily fertilized fields will contaminate water in P which will induce eutrophication in fresh water (Andraski and Bundy, 2003). Despite animal production and manure management is a key element to manage phosphorus in soil and water, maize residues are rich in P and can be detrimental for water quality (Arbuckle and Downing, 2001). The difficulty to recycle phosphorus is again reinforced by the globalization of the trade across the world (Nesme et al., 2018) while the demand is increasing worldwide, especially for bioethanol production in the US (Cordell et al., 2009).

c) Biodiversity

Soil biodiversity is known to be linked with a better soil structure, that allows a better nutrient and water supply to the crop (Kazemi et al., 2018). However, a direct link between soil microorganisms diversity, soil functioning and productivity should be made cautiously because of the high resilience of soil microbiome (Pulleman et al., 2022; Vazquez et al., 2021). The trade-off emphasized, for example, by Larsen et al. (2014) between microbial biomass and yield shows that a better ecological functioning does not necessarily provides better yields. It can also be linked with the better resistance of the conventional cropping systems that maintain high yields despite adverse conditions, as identified by Dardonville et al. (2022). Cropping practices such as reduced crop diversity and important use of chemicals (mineral fertilizers and

pesticides) reduce soil microbial diversity (Christel et al., 2021). The reduced diversity and abundance of soil microbiome under maize monoculture is largely confirmed by several recent studies (*e.g.* Jun Chen et al., 2018; Fu et al., 2019; Guo et al., 2021; Tian et al., 2019; G. Wang et al., 2021): crop rotations, cover crops and intercrops all improves soil microbiome.

Effect of deep tillage under MBCS remains unclear since some studies showed similar levels of activity or abundance under various tillage options (Anna et al., 2017; Zhang et al., 2022) and others showing a higher activity under reduced or no-tillage treatments (Gottshall et al., 2017; Jia et al., 2021). These contrasted results can be explained by the variability of the approaches and the type of measures. Some studies shows for example that it is the ratio between fungi and bacteria and, more generally the microbial community composition that can be affected by tillage and not necessarily the total microbial biomass (Behnke et al., 2021; Huang et al., 2013). Other practices, such as cover crops, influence the presence of soil microorganisms (White and Weil, 2010).

The negative effects of tillage on earthworms abundance and activity in MBCS is more clear with most of the studies showing a reduced abundance or activity of earthworms in conventionally tilled MBCS (Carter et al., 2002; Jordan et al., 1997; Katsvairo et al., 2002) even if not all studies conclude with a significant difference (Rosas-Medina et al., 2010). Earthworms were less influenced by crop rotation in respect with tillage, despite some crops such as cotton seems to have a detrimental effect on earthworms populations (Ashworth et al., 2017).

Recurrent and intensive use of herbicide was shown to affect the functions of soil microbiome in maize monoculture over time (Seghers et al., 2003). In the short term, nicosulfuron alone affected arbuscular mycorrhizae only at high doses (Karpouzas et al., 2014). However, Koçak and Cenkseven (2021) demonstrated that mixtures of registered herbicides reduced by -3.7% to -15% (according to the herbicide mix composition) microbial activity of soils cropped with maize in the weeks following their application. Seed treatments, the dominant practice for disease and soil pests management, also alters soil microbiome that could reduce maize stress tolerance (Nettles et al., 2016). As a consequence of absence of tillage and chemicals on a long term study, Larsen et al. (2014) obtained the highest microbial biomasses in organic no-till, followed by organic till then by conventional no-till.

Use of herbicide also induced the rising issue of herbicide-resistant weeds in maize production. Herbicide-tolerant weeds are present in at least 30 countries including all major producers (Hulme, 2022; Liu et al., 2019). In average per country, 5 resistant species are present. US reaches the maximum of 27 resistant species among which palmer-amaranth being the most common (Hulme, 2022). The resistant species increase in conventional MBCS since a limited number of herbicide molecules are used frequently on MBCS (Liu et al., 2019): glyphosate, 2,4-D or dicamba on GM tolerant crops (Nandula, 2019) and also S-metolachlor on non-GM crops. The introduction and widespread diffusion of GM-maize largely favoured the emergence and expansion of glyphosate-resistant weeds (Nandula, 2019) and pushed the farmers to increase herbicide doses applied (Benbrook, 2016).

4. Soil composition and structure

a) Carbon storage in soils and soil stability

Continuous maize production or other MBCS have an interesting potential of carbon storage, despite rotations including meadows can be better (Drury et al., 1998). Soil organic carbon greatly influences aggregate stability (Yan et al., 2022). Nevertheless, intensive MBCS have the advantage to bring back to the soil an important amount of carbon-rich biomass after grain harvest when stover is buried despite conventional tillage can affect this beneficial result (J. Chen et al., 2018; Chen et al., 2020). In some regions like China, stover is frequently exported for animal feeding (Huifang et al., 2014; Meng et al., 2006) which can significantly reduce soil carbon content (Li et al., 2021). Nouwakpo et al. (2018) showed that soil stability was better on maize monoculture in respect with soybean monoculture, soybean/maize rotation or other maize/legumes rotations (J. Chen et al., 2018), especially because of higher C/N ratio of maize stover. In the contrary, it is enhanced for maize-wheat rotations (Kan et al., 2022). Finally, ability of maize grown for biofuel to store carbon in soil is much reduced in respect with other energy crop such as switchgrass (Follett et al., 2012).

Considering soil stability, crop rotation – except when it includes perennials – remains of secondary importance compared with tillage. Indeed, tillage reduction overperforms crop rotations to improve soil stability in the majority of the studies (*e.g.* Nouwakpo et al., 2018; Paul et al., 2013). These studies emphasize that improved soil stability is always linked, in MBCS, with reduced tillage and presence of residues in soil surface.

Indeed, deep tillage reduces soil stability and buries crop residues. Moreover, it can enhance soil compaction under the tilled zone if done in too wet conditions (Hamza and Anderson, 2005; Tubeileh et al., 2003). However, in the short term, ploughing tends to increase maize growth in most of the MBCS, notably because a higher porosity is present.

Finally, pesticides applied on MBCS fields move through the soil before their degradation, volatilization, run-off or lixiviation (Alletto et al., 2010). Their persistence in the soil is very contrasted according to soil composition, physical and chemical properties of the pesticide considerer. In the Chinese Corn Belt, the pesticides applied on conventional MBCS are present in soils at worrying levels (Wang et al., 2020). Agriculture management also influences the presence of pesticides residues in soil as higher presence of organic residues on the surface will most likely increase their persistence in soil (Alletto et al., 2010; Cassigneul et al., 2016).

b) Soil erosion

Because of adverse crop practices such as bare soil during the fallow period and intensive tillage amplified by climate change, erosion globally increases worldwide (Larsen et al., 2014; Li and Fang, 2016; Nouwakpo et al., 2018). 80% of the cropland soils worldwide are subject to erosion with an average of 30 t ha^{-1} but extreme values going up to 400 t ha^{-1} far more than the accepted sustainable threshold of 0.5 to 1.0 t ha^{-1} (Pimentel and Burgess, 2013). If China and Europe are more susceptible to water erosion, US is affected both by water and wind erosion where soils of several regions are supposed to have lost 40 to 50% of their total fertile soil (Pimentel and Burgess, 2013). Row crops such as maize are particularly susceptible to erosion since they leave for a long time uncovered soil, before and during their cultivation (Pimentel and Burgess, 2013).

Soil erosion is dramatic for agriculture sustainability since it reduces water and nutrient availability, soil organic matter and soil depth (Pimentel and Burgess, 2013).

The MBCS in Europe, US and northern China have a great domination of spring crops in the rotations, up to 100% in the case of continuous maize or soybean-maize rotation. In those rotations, soil is covered only with stover during winter or can even be bare when deep tillage occurs before winter or if stover is removed. The absence of vegetation in the field during winter increases the risk of water or wind erosion, especially in the case of conventional tillage (*e.g.* Raczkowski et al., 2009). Indeed, the wide adoption of conservation tillage in the US reduced the average soil erosion from 16.4 t ha^{-1} in 1982 to 10.8 t ha^{-1} in 2007 (Pimentel and Burgess, 2013). Leaving bare soil in winter is very detrimental for soil conservation. (J. Wang et al., 2021) observed, in North China Plain, that conventional MBCS registered soil losses going from 1.2 to 22 t ha^{-1} depending on the year while (Laloy and Bielders, 2010), in Belgium observed soil losses during intercropping ranging from 0.0 to 42.1 t ha^{-1} (median value of 16.2 t ha^{-1}). In both studies, losses were also recorded during maize development, inducing that erosion effects continue after winter.

5. Water quality

Conventional MBCS reduce water quality from suspended soil, nitrate, and pesticides.

Erosion causes water turbidity because of suspended soil in water. Suspended soil is a major cause of water quality degradation per se but also because it generates further chemical degradations with pesticides adsorbed on suspended particles (Bilotta and Brazier, 2008)

The 45% of China groundwater samples had nitrate concentration above 50 mg/L that is the World Health Organization potability norm (Ju et al., 2006). All crops considered, NUE in China is one of the worst in the world (25%) because of a high use of mineral N (400 kg ha^{-1} in overall these last years) that continues to increase and overall moderate yields. (Ren et al., 2021) showed that N level was not correlated with yield: in their study, N supply varied by 48% while yield only by 14%, indicating an overfertilization. These low NUEs induce high charges but low income that can discourage pluriactive farmers to crop their land (Zhang et al., 2022).
In comparison, NUE is 52% in Europe with a N-fertilization that notably reduced since the 90's (*e.g.* -25% in France, -64% in the Netherlands, -75% in Greece) while yield continued to increase or to maintain (Lassaletta et al., 2014; Velthof et al., 2020). NUE is 68% in the US where fertilization stagnated around 175 kg ha^{-1} since the early 2000's while yield continued to increase (Lassaletta et al., 2014; Zhang et al., 2015).
Conventional MBCS are known for their important use of mineral nitrogen. Moreover, maize area is concentrated in alluvial soils particularly susceptible to transfers to the watersheds and rivers. High risks exist when the fertilization excess is greater than 75 kg N/ha, which might often be the case in US but also in China (Tenorio et al., 2020). Moreover, as soil remains bare for a long period in conventional MBCS (at least in Europe and US), nitrate leaching from a conventional maize field can be high (*e.g.* 30 to 75 kg ha^{-1} in Ochsner et al. (2018) study, 50 kg ha^{-1} in Klocke et al. (1999) study) especially under conventional tillage (Dai et al., 2021; Power et al., 2001). Continuous maize does not worsen performance in respect with other short

rotations such as soybean-maize (Lamb et al., 1998; Ochsner et al., 2018), or only slightly (Power et al., 2001).

Pesticides from agriculture uses can contaminate water through runoff that transports pesticides through bounded residues with soil particles but also in solution (Alletto et al., 2010). Runoff is thus linked with erosion. The other contamination way is through leaching, vertical transport down through the soil profile. Conventional MBCS are particularly detrimental for pesticide – and herbicide – water contaminations since i) their application occurs early in the cropping season, when there is not much crop water consumption. The first drainage or runoff events are thus highly susceptible to be concentrated in herbicides (Ghidey et al., 2005). ii) Herbicide molecules characteristics, poorly adsorbed on soil organic carbon, induce a higher susceptibility to transfer than other pesticides and iii) cropping management on conventional MBCS exacerbates the risks because of tillage, fallow period and irrigation management (Alletto et al., 2010). Contamination of water under conventional MBCS have been largely reported (*e.g.* Lamb et al., 1998; Marín-Benito et al., 2018; Schreiber, 1992) and are increased when several applications occur in MBCS (Vidotto et al., 2022), as is increasingly the case. (de Souza et al., 2020) reported that atrazine and metolachlor, both molecules particularly applied to conventional MBCS and soybean, are the most detected pesticides in surface water worldwide. There is no clear evidence that conventional tillage *per se* enhances both leaching and runoff but MBCS that leave mulch and or residues on the surface reduces runoff losses (Alletto et al., 2010). Better managing soil water content through cover crops present during winter (Meyer et al., 2018) would help to reduce contamination risks.

6. Air quality

a) Pesticides

Few studies exist on the volatilization of pesticides in the atmosphere after their application. Presence of pesticide in the air is variable according to the molecules, soil properties and conditions of applications. Conditions of applications are also important to consider as wind and dry soils can enhance pesticide volatility (Alletto et al., 2010). Some studies made on conventional MBCS showed that molecules present on seed coating volatilize during seeding and contaminate large areas after redeposition (Balsari et al., 2013). In a study on maize field sprayed with S-metolachlor, a common maize herbicide, Bedos et al. (2017) showed that 3 to 10% of the applied dose could be volatilized. Other studies on maize herbicides, alachlor, another chloroacetamide herbicide, and pendimethalin also showed an important ability of herbicide to volatilize (Briand et al., 2003 ; Ducroz, 2019).

b) GHG-emissions and energy consumption (figure I.12)

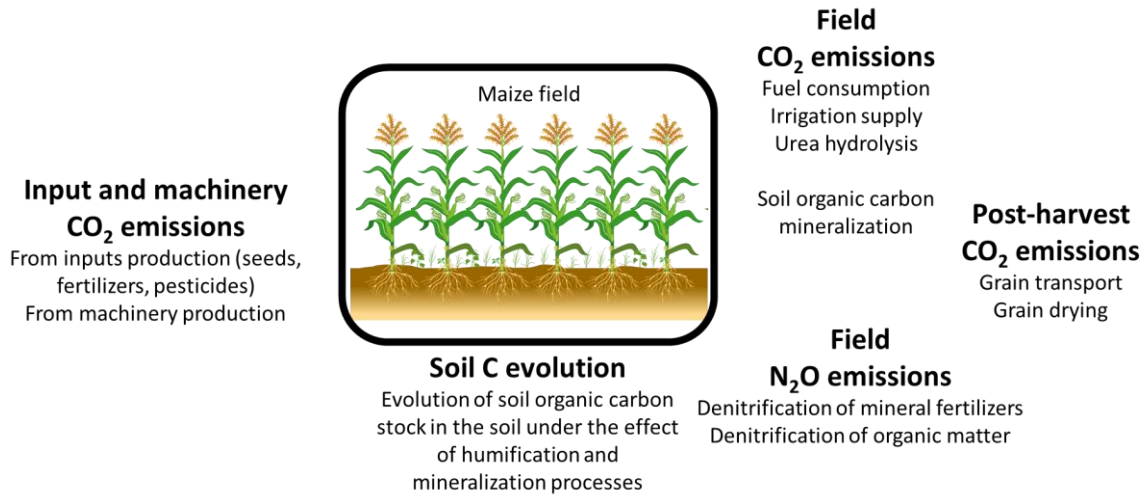


Figure I.12: Main elements to characterize GHG emissions of MBCS, inspired from (Juarez-Hernandez and Sheinbaum Pardo, 2019)

Overall, nitrogen fertilization is a large contributor to the greenhouse gases (GHG) emissions recorded on conventional MBCS since N-fertilizers need a lot of energy to be synthetized and are also largely responsible for N_2O soil emissions after their spread (Jacobs et al., 2017; Juarez-Hernandez and Sheinbaum Pardo, 2019; Konieczna et al., 2021; Tan et al., 2019; Yousefi et al., 2014).

Conventional MBCS are particularly responsible for these emissions because of their high – often excessive – N-fertilization as shown in China by (Mueller et al., 2012). Urea, the major fertilizer used in conventional MBCS also induces more emissions than ammonium-nitrate (Guardia et al., 2017).

If conventional tillage uses more fuel than conservation tillage and thus shows higher CO_2 emissions (Fathi et al., 2020; Juarez-Hernandez and Sheinbaum Pardo, 2019; Salamanca-Fresno et al., 2022), it is not necessarily the worst system as conservation tillage is most likely susceptible to increase N_2O fluxes (Tan et al., 2019). Globally, reduced tillage systems can be more efficient than conventional systems but adaptations are needed and trade-offs between energy balance and productivity need to be considered (Fathi et al., 2020; Juarez-Hernandez and Sheinbaum Pardo, 2020).

Irrigated systems enhance GHG emissions because irrigation needs energy *per se*, especially when pressurized water (sprinkler irrigation) is used (Guardia et al., 2017) and also because these systems tend to use more N-fertilizer and pesticides (Juarez-Hernandez and Sheinbaum Pardo, 2020, 2019). Irrigation was estimated to account from 14 to 21% of total emissions in conventional MBCS worldwide (Zheng et al., 2019). At the US scale, it was estimated at 0.2 to 3.8% in the total energy consumption by Kim et al. (2014) meta-analysis. Huge differences can exist worldwide according notably to the depth from where the water is pumped. Juarez-Hernandez and Sheinbaum Pardo (2019) showed that pressurized irrigation was the most GHG transmitter system followed by surface irrigation then by drip irrigation. Pressurized irrigation can represent up to 75% of the GHG-emissions in some areas where water is less accessible.

In the great majority of the studies, fuel emissions linked with field work remains moderate (6 to 10 %), except in rainfed systems with very low emissions (Jacobs et al., 2017; Juarez-Hernandez and Sheinbaum Pardo, 2020).

Irrigation impact on N_2O emissions is still debated since Zheng et al. (2019) meta-analysis explicitly assumed that N_2O emissions are lower in irrigated MBCS, it is in total contradiction with the statement of (Trost et al., 2013). Trost et al. (2013) found that irrigated fields with N-fertilization above 48 kg ha^{-1} (which is the case of almost all maize fields in China, US and Europe) increases by 87% their N_2O emissions per hectare. The authors also observed that irrigation caused greater in N_2O emissions when greater mineral-N was applied (Trost et al., 2013).

Grain maize is often harvested before the grain moisture is 15%, the commercialization norm. The average maize grain moisture at harvest is 18 to 24% (Wilson et al., 2017). Drying grains is thus necessary to store grains safely for several months. To improve grain quality, drying in cribs is almost stopped and drying is now largely done, at least in western Europe and US, directly in the grain storage facilities, at high energetical and monetary costs (Schnubel, 2020). (Giuliano et al., 2016) showed that drying grains represented 6 to 22% of the total energy use in a conventional MBCS of south-western France.

7. Climate change

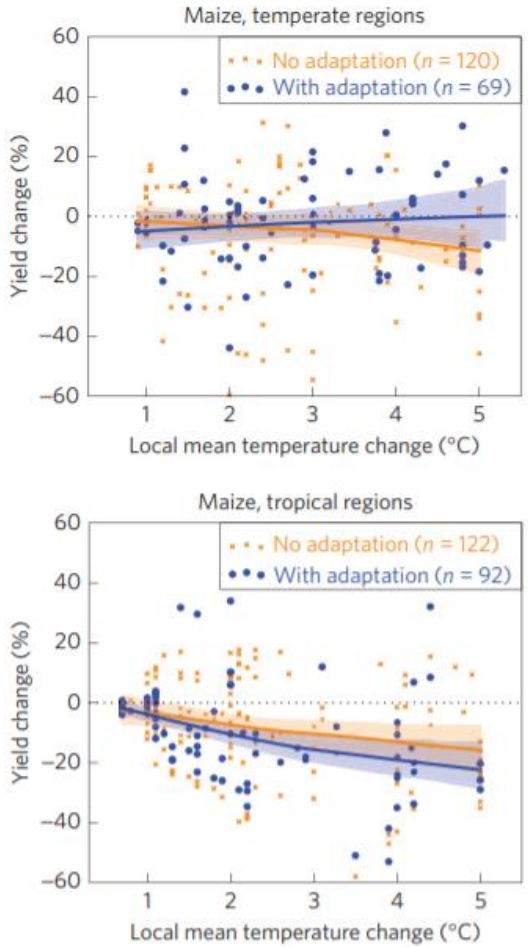


Figure I.13: Impact of climate change on maize yield in temperate and tropical regions, according to (Challinor et al., 2014)

Global climate change reduced by 3.8% maize productivity between 1980 and 2018 (Lobell et al., 2011). Global climate change will increase in next years, which will influence all sectors including agriculture. The magnitude of the impact will depend of the intensity of climate change in terms of temperature and precipitations. Under <2°C temperature increase, some regions could be beneficial of climate change but, above that threshold, a global reduction of agriculture productivity is expected and maize is evaluated as one of the most sensitive crop worldwide, especially under tropical climate (Figure I.13, Challinor et al., 2014). (Gaupp et al., 2019; Porter et al., 2019) estimated that maize is one of the most susceptible crop, with a 10.8% productivity reduction, especially under tropical climate. Under temperate regions, adaptations of maize cropping at the field level (varieties, sowing dates, irrigation…) could maintain maize yields up until +5°C but there is uncertainty on that threshold and food security would be largely threatened because of important losses on other crops and in other regions (Challinor et al., 2014). In north-eastern China, extreme events such as severe drought or heavy storms already increased and often impacted maize yields (in 47.6% of the cases for severe droughts and 13.3% for heavy storms) (Song et al., 2020). Y. Liu et al. (2020) estimated that an increase in temperatures above 1.5°C will negatively impact maize yields in China because of a reduction

in water availability. In the US, a global decline of maize yield is expected in the Corn Belt because of the presence of extreme temperatures during maize development (Johnston et al., 2015). In Europe, maize is the only crop with a significant yield reduction of 6% under climate change, despite a variability exists with a +14% productivity in northern Europe and a -11% in southern Europe (Knox et al., 2016), essentially because of drought stress increase (Webber et al., 2018). In all the regions, abiotic stresses (extreme heat during flowering, drought, extreme rainfall events…) are expected to be the main drivers of the yield reduction. Moreover, this alternation of droughts and extreme rainfalls that will increase in next years is also very detrimental for soil erosion (Li and Fang, 2016).

Some European regions such as Greece already experience heat waves that exacerbate yield variability (Schils et al., 2018). Increased yield variability was also emphasized by (Brisson and Levrault, 2012) in their model study for France. The authors also conclude that climate change will reduce yields by 1 to 1.5 t ha^{-1} in the near future because of a shortened vegetative period. On the other side, the need for irrigation will increase by 40 mm ha^{-1}. That reduced yield combined with more irrigation would lead to a lower economic return, inducing a surface reduction in the main production areas, that could be compensated by areas extension in northern regions. Climate change will also provoke a shift in weed communities (Chauvel et al., 2021) and pests development such as European Corn Borer that is expected to colonize much more northern Europe, increasing again the risk of *Fusarium sp.* (actual and new species) contaminations of grain maize (Miedaner and Juroszek, 2021). As a consequence, quality of the grain could diminish because of the development of mycotoxins, especially if temperature raises above +2°C (Battilani et al., 2016).

To limit the impact of climate change, maize cropping adaptations will be necessary. These include incremental adaptations in management (sowing dates, irrigation…) (Challinor et al., 2014), in the breeding of new varieties that could be able to maintain or even increase European maize production, especially if an increase of maize transpiration efficiency is modelled (Miedaner and Juroszek, 2021; Parent et al., 2018). However, when water availability is taken into account (Brisson and Levrault, 2012), impact of varieties or sowing date changes (sowing date is expected to advance by 1 day every 4 years) could be limited. For example, in France, later varieties might not be sown because they would imply an increased irrigation. The same authors indicate that a benefit of climate change for MBCS in temperate climates would be the reduction of energy and money consuming grain drying since maize would be much drier at harvest time. However, climate change could be an opportunity to more transformative changes in MBCS such as a facilitation to include winter cereals in rotation in maize usually cropped continuously because of earlier maize harvests (Brisson and Levrault, 2012; Landau et al., 2021).

Impacts	Sensitivity of conventional MBCS
Profitability	 Can be highly profitable but sensitive to global market
Irrigation water (for irrigated MBCS only)	 Very important uses in some regions, that limit the availability of water in aquifers
Phosphorus	 Not the crop with the highest requirements but high yields and few recycling, especially in grain maize
Soil biodiversity	 The importance of corn stover permits to maintain some soil biodiversity but frequent tillage is detrimental
Herbicide tolerant weeds	 Very important for GM maize in monoculture, reduced for more “diversified” systems without GM crops
Carbon storage in soils	 Better for reduced tillage MBCS, maize brings important amount of high C/N stover
Soil erosion	 Important stover with high C:N ratio allow to maintain C in the soil but soil remain bare during winter
Water quality	 Pollution because of herbicides and nitrate
Air quality (pesticides)	 Pollution because of herbicides and urea volatilization
GHG-emissions and energy use	 High impact of irrigated MBCS, intensive in energy (tillage, fertilizer production, drying…)
Susceptibility to climate change	 Adaptation strategies might not be sufficient

Table I.2: Dashboard of performances of MBCS on major environmental stakes and their variability. On the Likert scales, red indicates a low performance of conventional MBCS, yellow/orange is an intermediate performance and green represent a good performance. The length of the arrow is an estimation of the variability of the performance.

III. How to limit MBCS environmental impacts and improve its sustainability in temperate climates?

Despite an interesting economical profitability, conventional MBCS are characterized by low environmental performances in respect with climate change and environmental impacts on all the environment compartments (air, water, soil and biodiversity) (Table I.2). Nevertheless, several levers have been developed by research to limit environmental impacts and thus improve sustainability of MBCS.

1. Tillage reduction

Conservation tillage is one of the key practices used to improve environmental performances of MBCS with both abiotic and biotic effects. It improves soil stability and reduces soil erosion through a concentration of soil organic carbon in the surface and a better soil aggregation (Endale et al., 2019; Fiorini et al., 2020; Raczkowski et al., 2009; Seitz et al., 2019). Conservation tillage can also improve soil water dynamics (Cueff et al., 2020; Jia et al., 2021; Pittelkow et al., 2015), allowing a consecutive reduction in irrigation, measured at 20% in farmers' fields by Grassini et al. (2011).

The higher presence of soil organic carbon in the top-soil horizon and the reduced soil disturbance also improves biotic functions of the soil such as insect predators regulation (Murrell, 2017) like *Spodoptera frugiperda* that is better controlled in maize under conservation tillage with maintain of the residues (Rivers et al., 2016). However, this role remains unclear while some other pests such as corn borer can be more present in reduced tillage systems (Meissle et al., 2010).

If no tillage reduces maize yield by 7.6% in average (Pittelkow et al., 2015), minimum or reduced tillage seems to be a good compromise to maintain yield even if it can also lead to some yield losses, as in Europe (Van den Putte et al., 2010). In a review on rainfed maize, (Rusinamhodzi et al., 2011) showed that conservation tillage requires often more mineral nitrogen than conventional systems, which has been also emphasized by Pooniya et al. (2021).

This higher nitrogen inputs could withdraw the identified potential of conservation tillage cropping systems to mitigate climate change with up to 50% of CO_2 emissions reductions (Salamanca-Fresno et al., 2022) all the more because reduced tillage cropping systems can increase N_2O emissions (Tan et al., 2019). Another limitation of the reduced tillage MBCS is their higher needs for herbicide spraying (Colbach and Cordeau, 2018), in link with the changes in the weed community (Murphy et al., 2006) and the absence of mechanical weeding.

Tillage reduction combined with other practices might be beneficial. Jin et al. (2017) and Tan et al. (2019) observed in the Chinese context that stover retention in the field improves the potential of reduced tillage. In a meta-analysis in the US context, Marcillo and Miguez (2017) emphasized that the beneficial effects of no-tillage are enhanced when cover crops are used, which has also be proved in temperate climate context (Alletto et al., 2022a; Blanco-Canqui et al., 2015). Cross slope cultivation (tillage in perpendicular in respect with the slope) is also an

affordable technique that can be implemented in MBCS, in complement with tillage reduction since it can allow a 7 to 23% soil loss reduction (J. Wang et al., 2021).

2. *Cover crops and intercropping*

Cover crops (CC) are now used as multi-service tools to improve cropping system performances (Couëdel et al., 2019). In many regions such as US Midwest or Central Europe, implementation of CC in MBCS is challenging because of the late termination of the crop and the adverse climate conditions afterwards (cold or frost) and the water pre-emption at the beginning of the maize cropping, especially if destruction is late (Alletto et al., 2022a; Blanco-Canqui et al., 2015; Meyer et al., 2018).

Nevertheless, once these obstacles are overcome, CC introduction appears to be a relevant tool to improve MBCS sustainability. It maintains or improves yield in the majority of the cases: in their meta-analysis, Marcillo and Miguez (2017) revealed that maize yield following a cover crop was maintained after grass species CC, increased by 21% after legume CC and by 13% after a mixture CC. The authors also showed that CC were especially efficient in improving yields when mineral N supply was limited on the following maize: +33% yield for maize fertilized with less than 100 kg N ha^{-1}, showing all the interest of CC in low-input cropping systems (Marcillo and Miguez, 2017). The additional economy on inputs can also help to overcome be socio-economic constraints (seeds cost, machinery or labour availability to sow or destroy cover crops) that limit CC use in MBCS.

Under MBCS, cover crop introduction (especially *Brassicaceae* and *Poaceae* based) helps to better manage mineral nitrogen. They can reduce nitrate leaching by 45% (Nouri et al., 2022) both through a reduction of drainage, evaluated at 32% by Nouri et al. (2022) in their meta-analysis, and less NO_3^- concentrated leachates (Ochsner et al., 2018). As a consequence, CC improves N uptake by maize (Komainda et al., 2018), which is also a benefit of intercropping (Fu et al., 2019). CC introduction in MBCS also helps to reduce water runoff and erosion (Laloy and Bielders, 2010).

Finally, introduction of cover crops can help in managing weeds when produced CC biomass is capable of outcompeting weeds (MacLaren et al., 2019; Osipitan et al., 2018). However, despite CC can improve crop productivity, the impact of CC on weeds remains of secondary importance in respect with tillage and weeding (Adeux et al., 2021). To have a significant effect on weed biomass, CC need to produce enough biomass (Adeux et al., 2021), which might be complicated if CC is sown too late. Osipitan et al. (2018) showed in their meta-analysis that a 50% weed biomass reduction for 4 t ha^{-1} CC biomasses, which is more probable to obtain with CC composed with a limited (1 to 3) number of complementary species (Baraibar et al., 2018; Smith et al., 2020). The choice of CC species need to be adapted if termination is done without herbicide. With species not necessarily adapted to mechanical termination, weed suppression effect for the next cash crop can be reduced by approximately 50% compared with a herbicide termination (Osipitan et al., 2018), especially if ploughing is not implemented. Satisfying cover crops mixtures terminations were obtained using an undercutter in organic maize fields with 16.6% yield increase (Wortman et al., 2013). On the other hand, some progresses are made with roller-crimper for cover crops terminations but it often needs at least an additional herbicide treatment to maintain yields (Alonso-Ayuso et al., 2020; Mischler et al., 2010).

3. Nutrient and water management

N-fertilization improvements worldwide on maize are largely needed with both reduction of N rates and NUE increase. Indeed, GHG-emissions from N fertilization are mainly soil N_2O emissions and account for 48 to 64% of the emissions while transport and application of N fertilizers account for 7 to 22% emissions of US MBCS as indicated by Kim et al. (2014) in their meta-analysis.

Huge improvements can be made in MBCS by improving N-management, especially in China (Chen et al., 2014, 2011) where the implementation of an Integrated Soil-crop System Management (ISSM). ISSM consists in adapting N-supply to the crop needs, considering the soil contribution to the N nutrition. ISSM also integrates modifications in sowing date and seed rate and the use of adapted varieties. Through ISSM, fertilization is adapted all along crop development and it could maintain high-yields while largely reducing N fertilizer dose, from 402 kg N ha^{-1} to 256 kg N ha^{-1}. Compared with the high-yielding practice, N productivity is improved by 50%, from 37 kg of grains per kg of N to 56 while N dose is reduced from 402 kg N ha^{-1} to 256 kg N ha^{-1}. If that management was applied on Chinese maize production, it could reduce the GHG-intensity from 333 kg CO2 eq t^{-1} to 452 kg CO2 eq t^{-1} for the common farmer practice (Chen et al., 2014). In the US, GHG-intensity was estimated at 231 kg CO2 eq t^{-1} in Nebraska irrigated and high yielding fields (Grassini and Cassman, 2012), which remains still an intensive system if one calculates the emissions per hectare, that make more sense in a finite world.

According to the data presented by Lassaletta et al. (2014) for all major crops including maize, NUE in China is situated at approximately 30% and is declining because of input use increase, NUE in the US is 66% and is slightly improving. NUE in France is 77% and is globally improving. In the countries with the highest NUE, Decision Support Tools (DST) could help in reaching higher levels of NUE and limiting environmental costs but they have to be well adapted to the region (Ransom et al., 2020). Still in the US, Millar et al. (2010) proposed a smart approach that could reduce N_2O emissions on maize by 50% using MRTN, the Maximum Return to N, that takes into account regional yields for variable N rates and an economic rate taking into account the maize and the fertilizer prices.

Adopting more nitrate-based fertilizer, rather than urea or ammonium based fertilizers, would also reduce N2O emissions. An application timing closer to the maize needs is also of great interest since 30% US maize acreage is N fertilized in autumn (Millar et al., 2010).

Irrigation management can both reduce GHG-emissions and irrigation water requirements. Grassini et al. (2011) showed that irrigation was in excess in 55% of the situations in western US and that pivot irrigation water supply was 41% reduced compared with surface irrigation, with no differences in yield. Therefore, by adopting pivot irrigation and managing better irrigation rate and timing could lead to a reduction of 32% of the annual irrigation water. A similar magnitude of 30% irrigation water reduction was found by Steele et al. (2000) in the US with a better irrigation management, notably allowed using tensiometers that inform of the available water in the soil. The adoption of drip irrigation might be interesting as the power needed is lower and, since not all the soil surface is watered, N_2O emissions are lower (T. Zhang et al., 2021). However, pivot irrigation generalization will increase the energy requirement of

irrigated MBCS. Improvements in irrigation efficiency can also be carried out by increasing carbon content, a major driver of soil water holding capacity (Grassini et al., 2011).

4. Maize cultivars

GM-maize varieties have shown their limits in terms of weed management. New crop varieties with multiple herbicide resistance traits are under development (Nandula, 2019) but their efficiency might be of short duration as weeds can easily develop resistances to multiple herbicides, as it is the case for *Lolium perenne* L. for example (Jinyi Chen et al., 2018). Moreover, weeds (such as *Amaranthus tuberculatus* L.) can develop metabolic resistances *ie* developing resistances for herbicide molecules such as S-Metolachlor that never encountered before (Strom et al., 2020).

GM-varieties development for other traits such as yield or drought-tolerance remain for the moment poorly commercialized, maybe because these traits are polygenic with low heritability (Paul et al., 2018). The development success of specific GM-varieties for these traits is doubted by some authors (*e.g.* Denison, 2011).

Varieties mixture have been poorly studied in maize but are supposed to be less beneficial in maize in respect with other crops such as wheat (Barot et al., 2017) and this was verified for yield in a high-yielding Chinese environment (Zhai et al., 2017). However, in more marginal environments, heterogeneous maize varieties or landraces are cropped by farmers who want to reclaim their breeding work and varieties (Fenzi and Couix, 2022).

To reduce the water demand of maize, the use of short maturity varieties can be a relevant tool to reduce (irrigation) water needs of maize, estimated at 25 mm per year by Grassini et al. (2011) in their western US analysis.

5. Mechanical weeding

Cultivated as a row-crop almost everywhere with row width from 40 to 80 cm, maize is a favourable crop for mechanical weeding. Several studies showed that mechanical weeding is a able to reduce largely weed infestations with efficacy situated between 65 and 96% for hoeing (Kunz et al., 2018; Pannacci and Tei, 2014) applied alone. Both studies showed that a slight efficacy improvement can be obtained in maize with additional tools added on the hoe such as ridging element, finger weeder or torsion weeder. Moreover, recent advances in machinery with the use of cameras that automatically guide the hoe can also improve weeding performances, from 65% to 78% for Kunz et al. (2018) and they also permit to accelerate the weeding operation, which reduces the important cost of mechanical weeding (Heydel et al., 1999).

The vast majority of the studies on mechanical weeding also include a comparison with mix weeding, a combination of herbicide application on the row-crop and hoeing. Herbicide application on the row on maize can occur at sowing or during the hoeing operation or both. Nevertheless, climatic conditions for herbicide application and hoeing can be antagonist thus herbicide application at sowing or at different timing with hoeing might be preferred. These techniques can reduce by more than 70% the herbicide applied on maize with an equal weed control in respect with herbicide broadcast (Heydel et al., 1999; Mulder and Doll, 1993;

Pleasant et al., 1994). However, it increases the cost of weeding, even if it is reduced in respect with mechanical weeding, at least for Heydel et al. (1999).

6. Crop diversification

Cover crops contribute to diversify the species grown in a field but they usually stay for a very short time in the field. Introducing new crops in intensified and high input cropping system such as conventional MBCS is an important way to improve their environmental performances (Duru et al., 2015b; Isbell et al., 2017; Viguier et al., 2021). According to the soil-weather context and the initial MBCS, diversification is variable according to the region: it is more based on small grain cereals in the US corn belt, on legumes such as soybean in China and with both legumes and small grain cereals in Europe, when the initial MBCS was a maize monoculture. Improved performances have been emphasized by several authors that diversely showed that MBCS diversification improved (i) maize tolerance to drought much more than no-tillage (Renwick et al., 2021), (ii) increased soil carbon content and soil stability (Yan et al., 2022), (iii) decreased input requirement such as pesticide, energy or irrigation water (Alletto et al., 2022c), and also (iv) helped to better manage weed flora, especially under no-tillage (Weisberger et al., 2019)

Even if from a general perspective, diversification does not reduce grain yield (Tamburini et al., 2020), that statement is challenged in MBCS because of the high grain productivity of maize, as shown by Alletto et al. (2022c) in southwestern France and by C. Zhang et al. (2021) in the North-China Plain. However, it could evolve according to climate change (Brisson and Levrault, 2012). If the diversified MBCS improved the N efficiency of the systems in North-China Plain, where the initial rate of mineral N was high (C. Zhang et al., 2021), NO_3^- lixiviation was worsen in a MBCS diversified rotation in southwestern France (Viguier et al., 2021).

However, there are many constraints to diversify MBCS. Path dependency is emphasized by (Roesch-McNally et al., 2018). It means that future decisions are dependent of old choices (Valiorgue, 2020). In the case of MBCS diversification, a farmer could not sow small grain because he does not have the material adapted to, because there is no possibility to store and easily sell these grain. It can also be limited by the risk aversion of the farmers (van Zonneveld et al., 2020).

Finally, a major constraint for MBCS diversification is the risk of profit reduction for farmers and their clients, as shown by Alletto et al. (2022c) in a region were small grains have reduced yields because of pedoclimatic constraints: winter hydromorphic conditions, high temperatures in spring. However, this risk was not identified by all studies on MBCS (Pelzer et al., 2012; Viguier et al., 2021) and it was much lower if the diversification process was accompanied with a transition to organic agriculture (Langemeier et al., 2020). The presence of livestock on the farm, a localization on more marginal lands are able to facilitate diversification (Roesch-McNally et al., 2018) as well as the climate change "perspective". Policies could encourage the diversification of the MBCS by strong incentives (Ricome et al., 2016; Roesch-McNally et al., 2018).

Crop diversification in MBCS can also be achieved through agroforestry and grass buffers inside the field even if that solution seems for the moment poorly explored in temperate climates, maybe because C_4 plants as maize are less productive in the shade. On a long-term experiment in the US, Salceda et al. (2022) observed that soil organic carbon increased by 0.31% in 20 years of agroforestry while it was only +0.09% in the conventional management. Z. Liu et al. (2020) and Peng et al. (2009) observed however promising results with notably an

improvement of water use efficiency under an apple tree-maize agroforestry system in respect with monocultures.

Table I.3: Strengths, weaknesses, opportunities and threats of conventional MBCS

Strengths	**Weaknesses**
Productive Profitable Technically mastered Adaptable to a wide range of climatic conditions	One of the main income of the farmers Important production costs, especially in irrigated cropping systems Delivers in groundwater or rivers a poor quality water Uses a lot of inputs A bad carbon balance: energy for pumping water from gourndwater Reduces biodiversity Enhances soil erosion Reduces soil structure, SOM
Opportunities	**Threats**
New areas of cropping (or double-cropping) because of global warming New market developments (biofuels), a global rise of the demand New knowledge in the biotic regulations in the cropping systems to introduce agroecology in MBCS Innovative techniques available (mechanical weeding, cover crops, intercropping, organic and conservation agriculture…) Development of new machines around reduced tillage Fulfilling yield gaps where it is important by increasing N uptake and N efficiency Development of biocontrol to limit pesticide use Development of new varieties	Grain maize price volatility Input price volatility Outbreaks of new pathogens, pests or weeds such as herbicide-resistant weeds Diminution of water availability, for rainfed and irrigated MBCS Global warming (for the most, heat and water stresses) Diminution of meat consumption that could reduce demand for maize Poor global aggregation of all the techniques together in cropping systems

Conclusion: a need for a global approach of cropping systems

While main advantages of conventional MBCS are technical and economical, the weaknesses and threats of that cropping system are mainly environmental (table I.3). Organic and conservation agriculture are both well-established forms of agriculture. If their purpose is to reduce the agriculture reliance on external inputs, they do not guarantee a better impact on the environment (Dardonville, 2021). They are not always integrally applied (cropping diversification in conservation agriculture ; Pittelkow et al., 2015) or blurry in their definition (tillage depth « authorized » in conservation agriculture). Above all, the application of their specifications is not an absolute guarantee of better environmental performances despite they have tendentially better environmental performances than "conventional agriculture", that is also a common denomination that encompasses a large diversity of practices.

For example, Cavigelli et al. (2013) review showed that organic agriculture improved several ecosystem services as compared to conventional cropping systems and no-tilled cropping systems such as soil organic carbon and soil N. However, some services were lost when animal manure was applied due to soil erosion and N_2O emissions. In a review dedicated to conservation agriculture, Giller et al. (2015) showed that the benefits on soil and water conservation of the three pillars of conservation agriculture (crop rotation, soil cover and minimum tillage) were present in some regions but not in others. Organic and conservation agriculture could be combined but this remains a challenge to implement on large areas (Vincent-Caboud et al., 2019). More and more authors (Boeraeve et al., 2020; Duru et al., 2015b; Therond et al., 2017a) claim to go beyond that approach of "labelled" agricultural forms. (Therond et al., 2017a) suggest also not to classify the agricultural systems according to their "agroecologiness" because of the confused practical definition of the concepts linked with agroecology.

However, there are plenty of options available (table I.3) to improve MBCS sustainability, reduce their environmental impacts and adapt them to climate change, mobilizing the framework of biodiversity-based agriculture (Duru et al., 2015b). In order to hierarchize and organize together the different agronomic options, the Efficiency-Substitution-Redesign concept could be used (Hill and MacRae, 1996). Efficiency improvement of irrigation water, nitrogen or pesticide used on conventional MBCS is already largely tested and applied by farmers, even if huge progress can still be done, partially thanks to technology development. Substitution of inputs with the highest negative environmental impacts is also largely done by farmers and research in MBCS with the implementation of mechanical weeding, and the substitution of ploughing with reduced or no tillage. However, few studies apply concomitantly these Efficiency and Substitution concepts in the wider approach of Redesign that is about to create a less vulnerable system that lies on a drastic reduction of the conventional inputs to rely more on ecological processes ("biodiversity-based") that benefit to the crop development. For example, the application of no-tillage in the case of Redesign will imply to modify the other components of the system related to that technique: cover crop introduction, rotation changes, timing, rate and form of nitrogen fertilization, weeding… Redesign is a systemic approach that includes Efficiency and Substitution levels. Redesign also integrates much more regional context to develop adapted situations. In consequence, higher levels of organization must be considered in the case of biodiversity-based agriculture (Therond et al., 2017a), it is also

important for research to understand how the designed system functions at the plot scale does to see if it is compatible with higher scales.

Multi-criteria assessment of the MBCS can be useful for balancing tradeoffs, defining best options for MBCS, and to orientate fundings towards sustainable cropping systems (Therond et al., 2017a). Multi-criteria assessment considers social, technical, economic and environmental performances of farming (Therond et al., 2017a). Multi-criteria assessment is, for a policy maker, the only way to make an informed choice according to possible trade-offs. A lot of methodology have been developed to implement multicriteria assessment, despite a lack in evaluation of causal indicators or impacts, that have a direct implication on sustainability (Soulé, 2022).

Despite the interest of both system approach and multi-criteria assessment, very few studies truly consider entire cropping systems with all the management components they include (rotation, varieties, timing and doses of inputs, cover crop, tillage…) and very few evaluate these options from a multicriteria point of view. Actual studies often implement only one (*e.g.* tillage) or two (*e.g.* tillage and cover crop) changes in respect with the conventional MBCS, leaving all the other parameters identical despite carry over of these techniques on the entire cropping system (N fertilization, weeding…) which could lead to biased results. When entire cropping systems are considered, the evaluation often considers only one (often, yield) or few indicators (weed biomass, erosion control, economic return…).

Cas d’étude – l’expérimentation systèmes de culture de Lamothe



I. Historique

Les expérimentations systèmes de culture sur le Campus de Lamothe, exploitation agricole propriété de l'Ecole d'Ingénieurs de PURPAN, ont débuté à l'automne 2010 sur la parcelle de Terreblanque afin de mettre au point et d'évaluer des systèmes de culture alternatifs à la monoculture de maïs conventionnelle. L'objectif prioritaire de ces systèmes était qu'ils permettent d'améliorer la qualité de l'eau dans le contexte du bassin Adour-Garonne. Les objectifs secondaires concernaient une réduction de l'utilisation des principaux intrants utilisés en maïs : produits phytosanitaires, eau d'irrigation et azote minéral. Les niveaux de ces objectifs étaient différents en fonction des niveaux de rupture mis en place en termes de diversification du système (alternatives en monoculture ou en rotation de 3 ou 6 ans) et de réduction du travail du sol (du labour au semis direct, en passant par le strip-till). La mise en place de ce dispositif a été permise grâce au projet ANR MicMac-Design (2010-2013) et au projet régional Maestria.

Au-delà des objectifs environnementaux, le dispositif avait pour objet d'acquérir des références techniques, économiques et environnementales sur des systèmes de culture en rupture avec les systèmes mis en place par les agriculteurs et de fournir les données nécessaires à la modélisation de ces systèmes de culture innovants encore méconnus. *In fine*, ce couplage entre expérimentations de terrain en station expérimentale et modélisation avait pour objectif d'extrapoler les résultats obtenus à d'autres situations pédoclimatiques et d'améliorer la compréhension de certains processus tels la dynamique des produits phytosanitaires dans les sols. Cet objectif méthodologique a guidé certains choix concernant le suivi scientifique (agronomique et environnemental) de l'expérimentation.

II. Projets et évolution des problématiques de recherche

Les systèmes de culture mis en place ont évolué au cours du temps (Tableau C.I), selon 4 reconceptions qui ont eu lieu à pas de temps régulier :

- 2010 (projet ANR MicMac-Design) : mise en place des six systèmes de culture issus des ateliers de co-conception « chercheurs » afin d'**améliorer la qualité de l'eau** : une monoculture de maïs conventionnelle, trois monocultures de maïs alternatives, une rotation courte de trois ans et une rotation longue de six ans
- 2014 (projet CASDAR CRUCIAL) : arrêt de la rotation longue pour privilégier des systèmes de culture en monoculture de maïs intégrant une réduction du travail du sol et des **cultures intermédiaires basées sur des associations crucifères et légumineuses** conçus lors d'un mini-atelier chercheurs
- 2018 (projet INRAE-ACAF VACCARM) : **intégration des problématiques de changement climatique et gestion quantitative de l'eau** plus explicitement dans le dispositif. Les monocultures de maïs avec les plus faibles performances ont été remplacées par deux rotations de trois ans issues d'un atelier réunissant techniciens, agriculteurs et chercheurs
- 2023 (projet CASDAR ALIAGE) : nouvel atelier de co-conception (agriculteurs, techniciens, chercheurs) afin de concevoir un système qui pallierait les limites agronomiques (gestion des adventices) des monocultures de maïs avec très peu de travail du sol et d'**étudier les impacts environnementaux d'un système de culture en agriculture de conservation des sols sans glyphosate**.

Tableau C.II : les systèmes de culture mis en place sur le dispositif système longue durée de Lamothe. En gras, les systèmes de culture dont les résultats sont présentés dans les chapitres II, III et IV. En hachuré, les systèmes de culture avec réduction du travail du sol

Nom du système de culture	Acronyme	Objectifs	Principaux leviers mis en œuvre	Années de mise en place												
				2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023
Monoculture de maïs conventionnelle	**MM_{Conv}**	S'approcher de la conduite régionale	Labour Désherbage chimique systématique Variété tardive Irrigation et intrants non limitants													
Monoculture de maïs atteignant les objectifs du plan ECOPHYTO avec couverture hivernale	**MM_{LI}**	- 25% CO_2 - 25% N_{min} - 25% - 50%	Labour Désherbage chimique localisé + mécanique Variété demi-précoce Culture interm. trèfle/ray-grass en relais			*non labour*										
Monoculture de maïs en semis direct et couvert hivernal	**MM_{CT}**	- 30% CO_2 - 25% N_{min} - 25% - 10%	Semis direct Désherbage chimique Variété demi-précoce Culture intermédiaire base féverole	*strip-till*	*strip-till*											
Rotation courte maïs-soja-blé tendre	**MSW**	- 50% CO_2 - 50% N_{min} - 50% - 50%	Un labour avant maïs Désherbage mécanique et chimique Stratégies de faux-semis et d'esquive Cultures intermédiaires				*orge-soja dérobé*	*orge-soja dérobé*								
Monoculture de maïs en strip-till avec couvert permanent	**MM_{Still}**	- 25% CO_2 - 25% N_{min} - 10% - 10%	Strip-till Désherbage chimique Variété demi-précoce Couvert permanent base trèfle													
Rotation longue sorgho-tournesol-féverole-blé dur-pois-blé tendre	RL	- 50% CO_2 - 75% N_{min} - 75% - 75%	Un à deux labours Désherbage mécanique et chimique Stratégies de faux-semis et d'esquive Cultures intermédiaires, espèces rustiques													
Monoculture de maïs sans produit phyto	MM_{0phyto}	- 25% CO_2 - 25% N_{min} - 25% - 100%	Labour Désherbage mécanique Variété demi-précoce Culture interm. trèfle/ray-grass en relais													
Monoculture de maïs en semis direct et couvert hivernal avec apport massif de compost au démarrage	MM_{CTOM}	- 30% CO_2 - 40% N_{min} - 25% - 10%	Semis direct Désherbage chimique Culture intermédiaire base féverole Apports massifs de compost (années 1 et				apport de compost	apport de compost								
Monoculture de maïs en strip-till avec couvert hivernal crucifère/légumineuse	MM_{Still2}	- 25% CO_2 - 25% N_{min} - 25% - 10%	Strip-till Désherbage chimique (dont glypho) Variété demi-précoce Culture interm. crucifère/légumineuse													
Rotation courte en agriculture biologique avec cultures destinées à l'alimentation humaine soja - maïs pop-corn - avoine	SAH	- 50% CO_2 - 100% N_{min} - 50% - 100%	Un à deux labours Désherbage mécanique Stratégies de faux-semis et d'esquive Cultures intermédiaires, espèces rustiques													
Rotation courte avec cultures valorisant l'élevage maïs ensilage - soja - orge	SEP	- 30% CO_2 - 75% N_{min} - 50% - 50%	Techniques culturales simplifiées Désherbage mécanique et chimique Apports d'effluents d'élevage Cultures interm. valorisables par l'élevage													
Rotation en ACS sans glyphosate	ALIAGE	- 50% CO_2 - 30% N_{min} - 30% - 50%	*Conception du système en cours*													

Les huit systèmes de culture testés en 2023 se répartissent selon un gradient de réduction de travail du sol et un gradient de diversification des assolements avec différents niveaux de rupture (Figure C.I). Concernant le travail du sol, le gradient se répartit d'un labour annuel à du semis direct en passant par du labour occasionnel, des techniques culturales simplifiées et du strip-till. Concernant la diversification, le gradient se répartit d'une monoculture sans culture intermédiaire à une rotation de cinq ans avec couverts en passant par des monocultures avec cultures intermédiaires et des rotations de trois ans avec cultures intermédiaires.

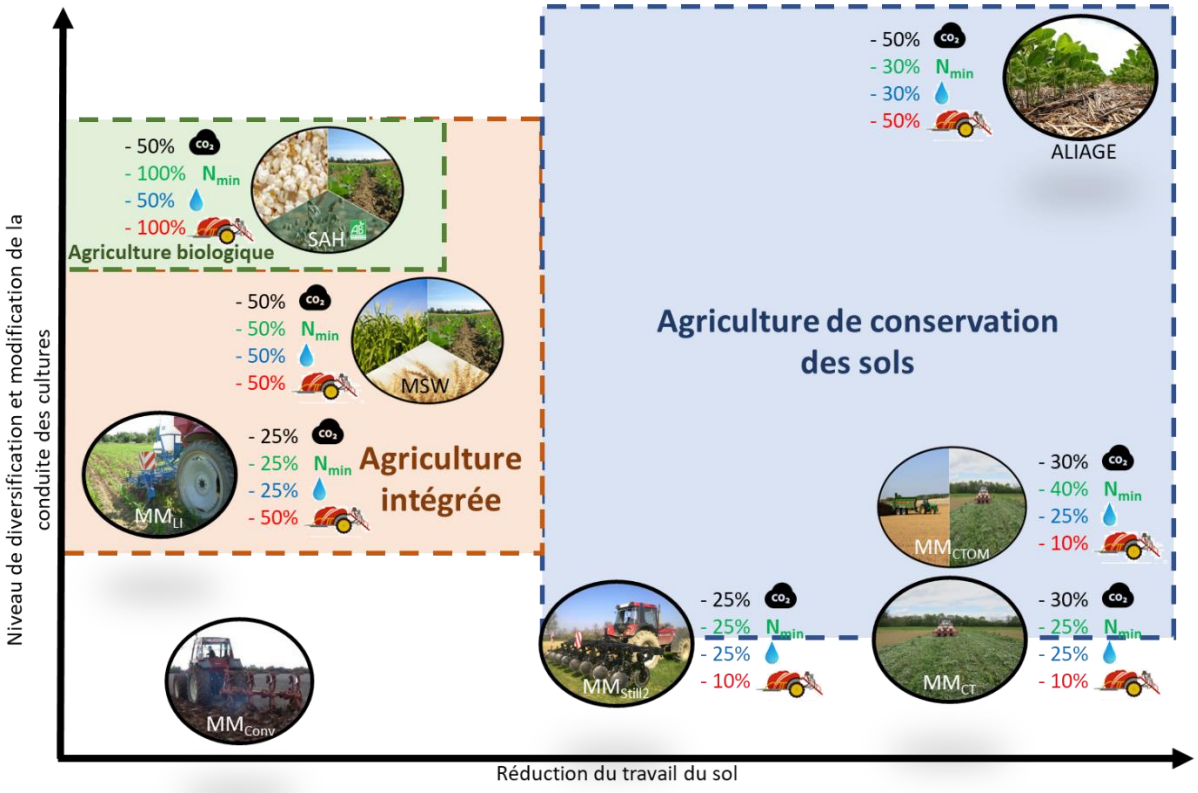


Figure C.I : les systèmes de culture testés à Lamothe en 2023

La diversification de la rotation et la réduction du travail du sol étaient deux leviers majeurs mis en œuvre dans l'expérimentation et qui ont structuré la reconception des systèmes. D'autres leviers importants, davantage orientés vers la substitution et l'efficience des intrants, ont également été utilisés, notamment l'utilisation de variétés tolérantes aux stress biotiques et abiotiques, l'introduction de désherbage mixte (chimique localisé sur le rang combiné à du désherbage mécanique), le pilotage des intrants (azote et irrigation notamment) via des outils d'aide à la décision, des décalages de dates de semis, modulation des doses de semis…

Au sein de chaque système de culture, plusieurs de ces différents leviers étaient mobilisés et organisés entre eux de manière cohérente afin d'atteindre les objectifs techniques, économiques et environnementaux fixés initialement, en tenant compte des interactions entre pratiques agricoles. Le choix des leviers mobilisés était réalisé en cohérence avec les objectifs. C'est l'objectif de cohérence entre leviers (e.g. réduction du travail du sol et couverture hivernale des sols) et objectifs fixés qui a orienté le choix vers un essai systémique et non analytique, qui aurait conduit à des modalités non pertinentes agronomiquement (*e.g.* un système en semis direct avec désherbage mécanique). L'objectif du système de culture MM_{Conv} était de se rapprocher d'une conduite et des performances régionales moyennes dans les systèmes de

culture maïsicoles, ce qui a été globalement le cas tout au long du dispositif (Figure C.2). C'est à partir de ces résultats de référence que les objectifs des systèmes de culture alternatifs étaient fixés.

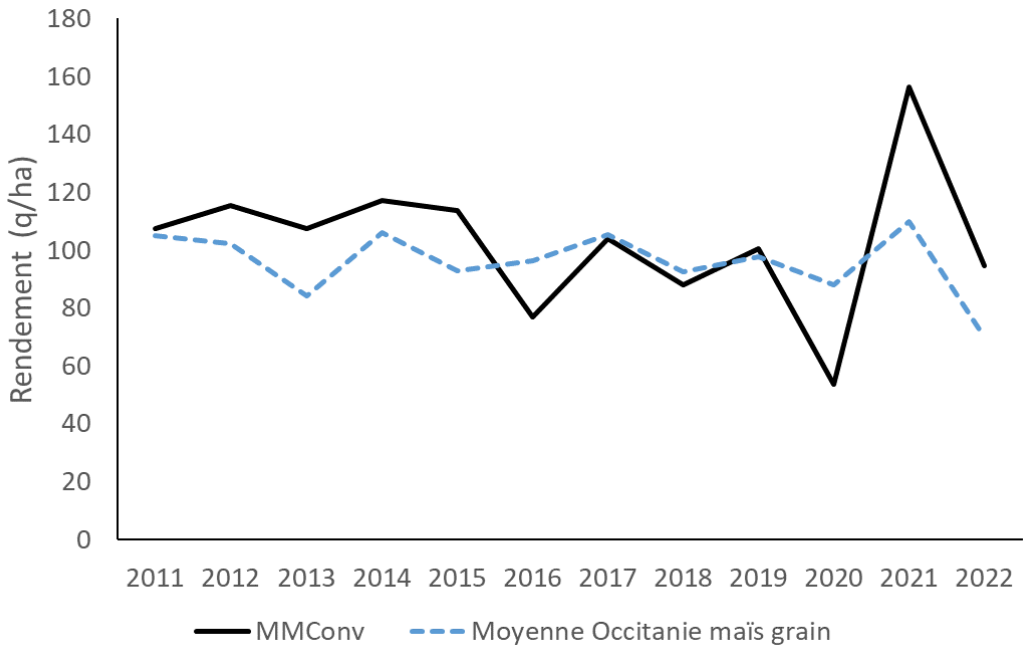


Figure C.2 : Rendements en maïs sur le système de référence du dispositif comparés à la moyenne régionale (Hermouet, 2023, communication personnelle)

Les éléments de reconception (rotation et travail du sol) étaient relativement fixes au cours du temps, exceptés les éléments cités dans le tableau C.1, et ne faisaient l'objet d'évolution majeure que lors des ateliers de re-conception. En revanche, les leviers de pilotage (outil de désherbage, variété…) du système pouvaient faire l'objet de modifications d'une année sur l'autre en fonction de la disponibilité technique d'éventuelles solutions innovantes (*e.g.* nouveau matériel disponible sur l'exploitation) et/ou des résultats obtenus.

Les opérations techniques étaient décidées à la suite de tours de plaine organisés régulièrement par les pilotes du dispositif, un ingénieur de recherche et un technicien de recherche en agronomie. Pour faciliter ces décisions tactiques, des règles de décision permettaient de décider des opérations techniques (*e.g.* seuil de développement d'une culture intermédiaire pour décider de son broyage ou non avant un labour).

III. Plan expérimental

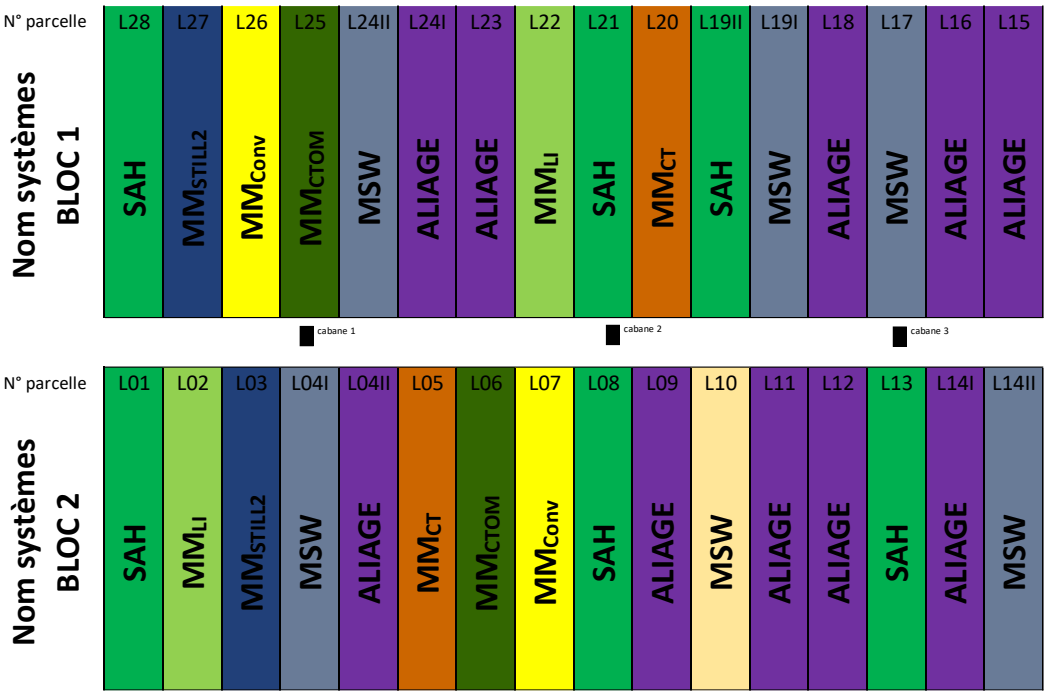


Figure C.3 : plan d'expérience

Les 32 parcelles du dispositif étaient réparties en deux blocs aléatoires complets (Figure C.3). Pour l'ensemble des rotations, tous les termes de la rotation étaient présents chaque année sur chaque bloc. Chaque parcelle expérimentale, unité statistique de référence, mesurait 720 m² (12 m x 60 m) afin d'utiliser des outils agricoles classiques. Un système d'irrigation avec une rampe frontale pivotante permettait d'irriguer indépendamment chaque parcelle avec des doses adaptées.

IV. Contexte pédoclimatique

Le dispositif expérimental est situé sur la parcelle de Terreblanque qui se trouve sur la deuxième terrasse de la Garonne. Son sol est néanmoins atypique pour la petite région car il provient d'alluvions récentes déposées par le Touch, la rivière (affluent de la Garonne) attenante à la parcelle.

Le sol est un luvisol de type limon argileux (Tableau C.2) de pente inférieure à 1%, avec un risque d'hydromorphie important pendant l'hiver.

	Argile (‰)	Limons (‰)	Sables (‰)	Matière organique (‰)	pH
Moyenne ± écart-type	354 ± 77	419 ± 36	227 ± 93	19,2 ± 2,0	6,9 ± 0,6

Tableau C.2 : texture moyenne du site expérimental, teneur en matière organique et pH

Un gradient d'argile Est-Ouest est présent sur la parcelle (Figure C.4), ce qui peut impacter les performances des systèmes de culture. Ce gradient peut également impliquer des états de parcelle différents entre les deux blocs et nécessite ainsi de faire des compromis dans les

décisions tactiques car les opérations culturales sont toujours réalisées en même temps pour deux parcelles d'un même système de culture.

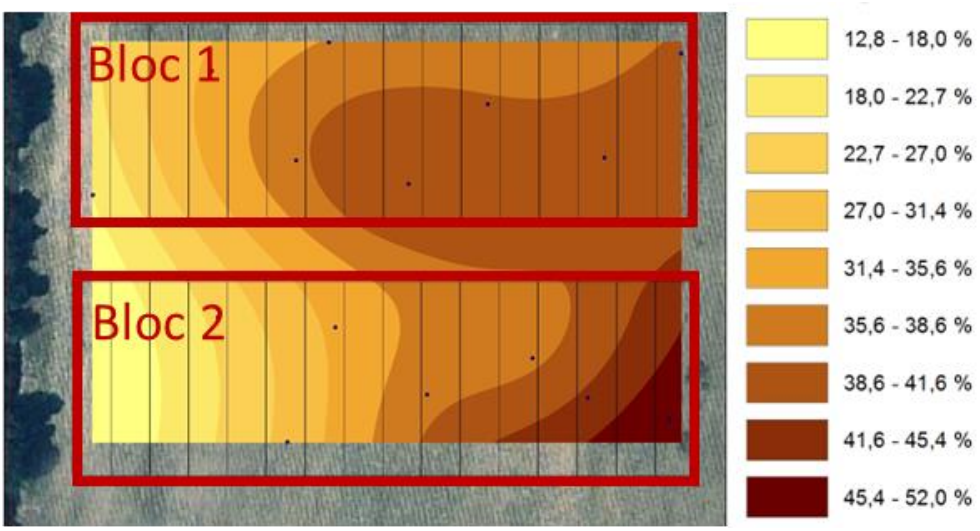


Figure C.4 : illustration du gradient d'argile présent sur le site expérimental (horizon 10-30 cm)

La parcelle était historiquement conduite en rotation blé-tournesol car dépourvue d'irrigation. Les sols sont néanmoins propices à des systèmes maïsicoles, y compris en monoculture (hydromorphie hivernale, somme de températures et ensoleillement élevés, mécanisable…).

V. Suivis scientifiques

Afin d'évaluer les performances technico-économiques des systèmes de culture mis en œuvre, l'ensemble des opérations techniques réalisées dans les parcelles sont collectées dans le détail (date de passage, tracteur et outils utilisés, vitesse de passage en rythme « de croisière », quantité et type d'intrants utilisés) dans un fichier Excel et reliées à des bases de données de prix (interne), de coût d'intervention (charges de mécanisation ; APCA, 2020), d'émissions de gaz à effet de serre (Camargo et al., 2013) et d'homologation d'utilisation des produits phytosanitaires (base de données accessible en ligne E-phy). La base de données d'itinéraires techniques permet ainsi de calculer un nombre important d'indicateurs économiques (marge brute, marge semi-nette…), de temps de travail ainsi que de caractériser des pressions (quantités de N, P ou K utilisées, indicateur de fréquence de traitement) ou des impacts (émissions de gaz à effet de serre) environnementaux.

Le suivi agronomique consiste en un suivi de la croissance et du développement de la culture et un suivi des bioagresseurs. Les dates des stades-clés des cultures (floraison, maturité) sont notés et les plantes sont prélevées tout au long du cycle de développement (pour le maïs, aux stades 6/8 feuilles, floraison et maturité ; pour les cultures intermédiaires, à destruction) afin de suivre l'évolution de leur biomasse sèche et de leur teneur en azote. Lors de ces prélèvements de biomasse, les adventices sont également prélevées, identifiées au niveau de l'espèce, passées en étuve, pesées afin de connaître leur biomasse sèche et analysées afin de connaître leur teneur en azote (2011-2020). Les maladies et ravageurs sont suivis de manière qualitative afin de prendre des décisions d'action mais ne font pas l'objet d'un suivi scientifique dédié. Afin de ne

pas biaiser les suivis et être représentatifs de l'état général des parcelles, 4 prélèvements de biomasse sont réalisés sur des quadrats prédéfinis au cours du temps. Ces quadrats sont positionnés dans la zone centrale de la parcelle (au moins 3m des bordures latérales et 15m des bordures de début et fin de parcelle) afin de limiter les effets de bordure (influence des parcelles voisines et espace nécessaire au lancement d'un outil de travail du sol). A maturité, au moins deux prélèvements récolte (grains uniquement) de 6 m² sont réalisés pour chaque parcelle.

Un suivi de la dynamique hydrique est également réalisé via des sondes de teneur en eau et des sondes tensiométriques (2011-2014) et des sondes capacitives depuis 2019. Le dispositif de suivi de la dynamique hydrique est complété par des plaques lysimétriques qui ont été installées dans toutes les parcelles en 2011, à 1m de profondeur sous une colonne de sol non perturbé (Figure C.5). Ces plaques sont maintenues à dépression constante équivalente à la capacité au champ (-0.33 bar) et connectées à des bombonnes permettant de collecter les lixiviats tout au long de la campagne de culture du maïs, à une fréquence d'une fois toutes les deux semaines environ. Le lixiviat collecté est ensuite conservé au froid durant la campagne puis analysé laboratoire pour connaître sa teneur en pesticides. Les teneurs mesurées permettent ainsi de renseigner l'impact des systèmes de culture sur la qualité de l'eau de drainage, qui est une originalité forte du dispositif. Du fait de remontées de nappe phréatique, le suivi doit fréquemment être interrompu durant l'hiver mais est généralement entièrement opérationnel du semis du maïs (avril) au mois de décembre.



Figure C.5 : installation d'une plaque lysimétrique sur le dispositif

Enfin, un suivi sol est réalisé en routine sur le dispositif avec des reliquats d'azote mesurés sur l'horizon 0-120 cm à la destruction de la culture intermédiaire/semis des cultures de printemps et à la récolte des cultures de printemps/semis des cultures d'hiver. Environ toutes les 3 à 4 campagnes, des suivis de sol (0-30 cm) sont réalisés afin de mesurer l'évolution de variables « lentes » telles que la teneur en phosphore, potassium ou calcium, le pH ou le taux de matière organique.

VI. Publications de rang A produites à partir de données issues du dispositif expérimental

- Giuliano S, Alletto L, Deswarte C, Perdrieux F, Daydé J, Debaeke P., 2021. Reducing herbicide use and leaching in agronomically performant maize-based cropping systems: An 8-year study. Science of Total Environment 788, 147695 (**Chapitre IV de la thèse**)
- Marín-Benito, J.M., Alletto, L., Barriuso, E., Bedos, C., Benoit, P., Pot, V., Mamy, L., 2018. Pesticide fate modelling in conservation tillage: Simulating the effect of mulch and cover crop on S-metolachlor leaching. Science of Total Environment 628, 10.1016/j.scitotenv.2018.02.144
- Adeux G, Giuliano S, Cordeau S, Savoie JM, Alletto L, 2017. Low-Input Maize-Based Cropping Systems Implementing IWM Match Conventional Maize Monoculture Productivity and Weed Control. Agriculture 7(9), 74 (**Chapitre III de la thèse**)
- Bedos C., Alletto L., Durand B., Fanucci O., Brut A., Bourdat-Deschamps M., Giuliano S., Loubet B., Ceschia E., Benoit P., 2017. Observed volatilization fluxes of S-metolachlor and benoxacor applied on soil with and without crop residues, Environmental Sciences and Pollution Research, 24:4
- Giuliano S., Ryan M.R., Rametti G., Perdrieux F., Justes E., Alletto L., 2016. Low-input cropping systems to reduce input dependency and environmental impacts in maize production: a multicriteria assessment. *European Journal of Agronomy,* Vol. 76, 160-175 (**Chapitre II de la thèse**)
- Alletto L., Pot V., Giuliano S., Costes M., Perdrieux F., Justes E., 2015. Temporal variation in soil physical properties improves the water dynamics modeling in a conventionally-tilled soil. *Geoderma*, 243-244, 18-28.
- Marín-Benito, J.M., Pot, V., Alletto, L., Mamy, L., Bedos, C., Barriuso, E., Benoit, P., 2014. Comparison of three pesticide fate models with respect to the leaching of two herbicides under field conditions in an irrigated maize cropping system. Science of Total Environment 499, 533–545. https://doi.org/10.1016/j.scitotenv.2014.06.143

Chapitre II
Evaluation multicritère de systèmes de culture à faible niveau d'intrants et impact sur l'environnement, alternatifs à la monoculture de maïs conventionnelle



Résumé du chapitre

Contexte

Les systèmes de culture maïsicoles sont confrontés à de nombreuses problématiques environnementales (gestion quantitative et qualitative de l'eau, émissions de gaz à effet de serre…) dans différentes régions de la planète et en particulier dans le Sud-Ouest de la France. Les approches proposées par la recherche pour pallier ces problématiques sont le plus souvent des expérimentations analytiques portant sur l'étude d'un ou au maximum deux facteurs combinés (travail du sol, fertilisation, choix variétal, cultures intermédiaires, désherbage…). Pourtant, ces différents facteurs sont en interaction forte dans un agroécosystème. Par exemple, la réduction du travail du sol nécessite d'adapter les doses et dates de fertilisation du fait d'une dynamique de réchauffement du sol différente des systèmes labourés et également de faire évoluer les pratiques de désherbage (choix du matériel, des substances actives…). Ainsi, il est particulièrement intéressant d'étudier ces facteurs de manière combinée au sein de systèmes de culture construits dans le but d'atteindre un ensemble d'objectifs et permettant ainsi d'évaluer des interactions entre techniques et de déterminer d'éventuels compromis entre objectifs (Debaeke et al., 2009). Enfin, lors de la mise en œuvre de systèmes de culture plus durables, la phase de transition est particulièrement critique et nécessite d'être étudiée finement par la recherche (Martin et al., 2018).

Contenu du chapitre

Ce chapitre porte sur la comparaison d'une monoculture de maïs conventionnelle avec trois systèmes de culture alternatifs mobilisant différentes combinaisons de leviers agronomiques. Cette évaluation est réalisée selon plusieurs dimensions techniques, économiques, sociales et environnementales. Cette évaluation porte sur les trois premières années de mise en œuvre des systèmes de culture et permet notamment d'évaluer la phase de transition d'un système conventionnel vers un système de culture plus durable.

Méthodologie mise en œuvre

Plusieurs points méthodologiques clés ont été nécessaires à la réalisation de cette étude. Tout d'abord, *i)* les systèmes de cultures mis en place sont issus d'*ateliers de co-conception* réunissant agriculteurs, techniciens et chercheurs. Ensuite, ces quatre systèmes de culture évalués ont été *ii) mis en place sur des parcelles expérimentales*, en deux blocs randomisés complets. Ils ont été mis en œuvre en vue *iii) d'atteindre des objectifs spécifiques, fixés lors de la phase de co-conception*. Les choix techniques étaient réalisés grâce au *suivi de règles de décision* et tenaient compte des objectifs des différents systèmes. Les objectifs des systèmes portaient sur les différentes dimensions de la durabilité et ont donc *iv) fait l'objet d'une évaluation multicritère*. Une originalité importante du dispositif est que l'évaluation multicritère réalisée était *v) quantitative* et s'appuyait sur des données collectées *in situ*, via la collecte des itinéraires techniques et en mesurant des indicateurs d'impact des pratiques agricoles (flore adventice, lixiviation d'herbicides…). *vi) L'analyse multivariée réalisée (Analyse Canonique Discriminante),* complétée par des analyses de variance, est une approche statistique relativement originale. Enfin, *vii) les représentations graphiques* sous forme de tableau de bord ou de diagrammes permettent de synthétiser un grand nombre d'informations de manière assez visuelle.

Principaux résultats

Les résultats économiques et sociaux de la monoculture mobilisant les leviers de la production intégrée sont similaires à ceux obtenus sur monoculture de maïs conventionnelle alors que, dans le même temps, les performances environnementales sont améliorées de manière substantielle (de 15 à 50%). Le système en rotation mobilisant également les leviers de la production intégrée permet lui aussi de largement améliorer les performances environnementales mais la rentabilité de ce système est plus faible. Enfin, le système en agriculture de conservation des sols s'est traduit par des performances techniques, économiques et environnementales bien inférieures durant cette phase de transition.

Portée des résultats pour la thèse

Ce chapitre permet de valider l'approche quantitative et multicritère d'évaluation de systèmes de culture expérimentaux pendant une phase de transition. Les résultats obtenus dans ce chapitre II sont remobilisés dans les chapitres III et IV de la thèse qui étudient ces mêmes systèmes sur une plus longue période. Ces deux chapitres à venir ont également pour objectif de détailler les processus sous-jacents pour mieux comprendre les résultats obtenus dans ce chapitre II, en particulier pour ce qui concerne l'évolution de la flore adventice et le devenir des herbicides.

Low-input cropping systems to reduce input dependency and environmental impacts in maize production: a multi-criteria assessment

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cite as : Giuliano S., Ryan M.R., Rametti G., Perdrieux F., Justes E., Alletto L., 2016. Low-input cropping systems to reduce input dependency and environmental impacts in maize production: a multicriteria assessment. European Journal of Agronomy, Vol. 76, May 2016, p. 160-175 https://doi.org/10.1016/j.eja.2015.12.016

Abstract

Intensification of cropping systems in recent decades has increased their productivity but affected air, soil and water quality. These harmful environmental impacts are exacerbated in Maize Monoculture (MM) and hasten the need for solutions to overcome the tradeoff between crop yield and environmental impacts. In a three-year cropping systems experiment, a conventional intensive maize monoculture (MM_{Conv}), with a winter bare fallow, deep soil tillage, non-limiting irrigation was compared to three Low Input Cropping Systems (LI-CS) designed as alternatives to the conventional system. They were managed with decision-rules implemented to reach specific objectives of input reduction. The LI-CS designed with Integrated Weed Management (IWM) techniques and other sustainable cropping practices, were: i) MM_{LI} – an IWM Low Input MM; ii) MM_{CT} – a Conservation Tillage combined with cover crop MM; and iii) Maize-MSW – an IWM maize grown in rotation with soybean and wheat. A comprehensive multi-criteria assessment was carried out to quantify the agronomic, economic, social, and environmental performances of each system. A canonical discriminant analysis of performance metrics revealed large differences between the four systems. Yields were significantly higher in MM_{Conv} (11.0 Mg ha^{-1}) and MM_{LI} (10.3 Mg ha^{-1}) than in Maize-MSW (8.6 Mg ha^{-1}) and MM_{CT} (7.8 Mg ha^{-1}). MM_{CT} had the largest weed infestation (density and biomass) despite the greatest use of herbicides. The Herbicide Treatment Frequency Index (HTFI), used to indicate differences in herbicide use, revealed that the MM_{LI} (HTFI=1.0) and Maize-MSW (1.1) halved the herbicide use as compared to the MM_{Conv} (2.1), despite having similar weed abundance levels. The LI-CS, especially MM_{CT}, produced high biomass winter cover crops and then less nitrogen fertilization was required as compared to MM_{Conv}. Gross margins in the MM_{LI} (1254 € ha^{-1}) and MM_{Conv} (1252 € ha^{-1}) were higher than the MM_{CT} (637 € ha^{-1}) and Maize-MSW (928 € ha^{-1}). MM_{LI} and MM_{Conv} had similar labour requirements. Water drainage, pesticide leaching, energy use, and estimated greenhouse gas emissions were higher in MM_{Conv} than in the LI-CS in most years. Results from this research show good potential for the MM_{LI} to reduce the environmental impacts of MM_{Conv} while maintaining its economic and social performance.

Keywords

Integrated Weed Management – water quality – cover crop – maize monoculture – agricultural systems

I. Introduction

Intensification and industrialization of agriculture in recent decades has led to great increases in food production but also to numerous undesirable environmental impacts such as biodiversity loss, soil degradation, and soil, water, air, and food pollution (Stoate et al., 2001; Babalola et al., 2007; Lichtfouse et al., 2009). In order to limit these negative externalities, several directives and plans have been approved and are promoted in Europe through the Common Agricultural Policy (CAP) (European Parliament, 2009; European Commission, 2013). In France, the national Ecophyto plan, started in 2008, reinforces the goal of the European Union to reduce the use of pesticides and aims to halve the quantity of pesticides used.

In the same time, productivity of agroecosystems in European Union has not to drastically decrease in order to meet the overall rising demand for food, feed, fiber, and biofuels (Lichtfouse et al., 2009; Vasileiadis et al., 2013).

This duality produces new challenges for agronomy, and there is an immediate need to develop practical solutions to reach these conflicting objectives. The ESR (Efficiency, Substitution and Reconception) strategy proposes three levels of action (Lichtfouse et al., 2009; Ricci et al., 2011). The "E" level concerns technical operations (e.g. localized herbicide spraying, reduced applied dose) that result in pesticide use reduction. However, it does not solve the problems of reduction of the number of pesticides authorized for use nor the resistance risks linked to their uses (Lichtfouse et al., 2009; Ricci et al., 2011). The "S" level proposes to substitute chemical inputs by other practices that reduce the environmental impact [e.g. genetic tolerance to pests; biocontrol by trichograms (*Trichogramma ostriniae*) to control European corn borer (*Ostrinia nubilalis*)]. However, this level does not address the ecological dysfunction that led to the widespread incidence of pests (Hoffmann et al., 2002; Ricci et al., 2011). The "R" level aims at reducing this dysfunction by a redesign of cropping systems through Integrated Pest Management (IPM). Unlike purely chemical methods, IPM's effectiveness lies in a complementary combination of "E" and "S" techniques that might only have a partial effect if employed alone. This management offers a promising solution to the trade-off between input reduction and yield preservation (Debaeke et al., 2009; Lichtfouse et al., 2009; Meissle et al., 2009; Ricci et al., 2011).

Practically, IPM principles are combined in innovative Low-Input Cropping Systems (LI-CS) to preserve a realistic and systemic management strategy and to study carryover effects of management strategies (*e.g.* introducing no tillage involves adapting sowing dates). This holistic approach takes into account the complexity and functioning of agro-ecosystems. LI-CS approach allows for multiple combinations of IPM techniques (Drinkwater, 2002; Meynard et al., 2003; Lichtfouse et al., 2009; Ricci et al., 2011). A multidisciplinary approach, often lacking, is needed to evaluate LI-CS because the decision-rules used to run them often have several competing goals including agronomic (e.g. yield, pest pressure), economic (e.g. gross margin), environmental (e.g. nitrate or pesticide leaching) and social (e.g. labour input, painfulness) (Schillinger, 2010).

Management of LI-CS involves decision-rules that prioritize specific outcomes to reach the LI-CS objectives. These rules are technical (e.g. to choose a method of weeding soon after crop

emergence) and form the *tactic* employed to reach an optimal management according to the *strategy*, which can be considered the general objectives for the system (*e.g.* reduce the use of herbicide by 50% whilst producing a profitable crop) and the constraints in which the system is held (*e.g.* maintain a stable soil seed bank, no-tillage). After every crop, these rules are evaluated and adjusted according to the results obtained as part of an adaptive management approach (Debaeke et al., 2009).

Several IPM methods are relevant for maize production including mechanical weeding (Melander et al., 2005), reduced tillage (Archer et al., 2008; Alletto et al., 2011), crop rotation (Liebman and Davis, 2000; Westerman et al., 2005; Sosnoskie et al., 2006), biocontrol (Hoffmann et al., 2002; Wright et al., 2002), cover crops for (i) weed control (Barberi and Mazzoncini, 2001; Nagabhushana et al., 2001), (ii) nitrogen management (Blevins et al., 1990; Justes et al., 1999), (iii) erosion reduction (Laloy and Bidders, 2010), localized spray weeding (Mulugeta and Stoltenberg, 1997), earlier varieties (Velasco et al., 2004), delayed planting (Williams II, 2006), optimized nitrogen (Sogbedji et al., 2000) and water management (Wang et al., 2001), etc. However, their adoption in Europe remains low because farmers have insufficient access to information about practical management strategies, poorly developed by agronomic research (Meissle et al., 2009; Vasileiadis et al., 2013).

IPM practices are however less effective against weeds compared to insect pests or disease (Buhler et al., 2000). Unlike with disease and insect pests (Tang et al., 2005), the economic efficiency of a herbicide application is difficult to evaluate due to misunderstandings about yield losses and soil weed seed bank evolution (Westerman et al., 2005). Since herbicides represent more than 90% of the total quantity of pesticides applied in maize in France (Agreste, 2013), it is assumed that weed competition is the major biotic stress in maize production. This may explain why chemical control remains the main weed control tactic used in maize production. It also explains the harmful effect of that cropping system on water quality (Barran and Goucy, 2013; Belmonte et al., 2005; Ghidey et al., 2005; Konstantinou et al., 2006; White et al. 2009), especially when irrigated, heavily fertilized and ploughed (e.g. Angle et al., 1993). Judging by the maize herbicide concentrations found in the surface waters, the degradation of water quality due to maize production is obvious in south-western France (Agence de l'Eau Adour-Garonne, 2013). This is the major maize-producing region of the country with 40% of the 1.6 million ha national acreage, second largest crop grown in France. With dry summers and low soil water storage, 80% of the maize crop of the region is irrigated. Due to the investment in irrigation and the high profitability of the crop, maize is mainly grown in conventional high-input continuous maize cropping systems that give high yields, around 10 Mg ha^{-1} (DRAAF, 2013).

This high-input system includes mineral N fertilization that represents 30 % of the total GHG emissions due to maize production (Kim et al., 2009). The combination, in the region, of N fertilization (190 kg ha^{-1} on average) and irrigation results in high nitrate (NO_3^-) leaching into surface and groundwater. Maize monoculture zones and the area of application of the EU Nitrates Directive (91/676/EEC), where nitrate pollution has been detected, are very similar in south-western France. At the cropping system scale, the implementation of the Nitrate Directive aims at reducing N fertilization amounts and at enhancing the use of cover crops.

The context is thus favourable to the implementation of maize based LI-CSs with low rates of herbicide, mineral N and irrigation water. However, the application of IPM principles

(especially those of IWM) to maintain a low weed population on maize, using rule-based management, is challenging. The purpose of this research was to evaluate the performance of three maize-based LI-CS aiming at reducing input (such as N, herbicides, fuel and water) dependency and environmental impacts, compared with conventional intensive monoculture. Ten indicators of sustainability were used to compare the agronomic, economic, social and environmental performance of the four cropping systems. Overall differences between cropping systems were estimated using CDA (Canonical Discriminant Analysis), which provided a way to visualize the differences among systems.

II. Materials and methods

1. Site description

The experiment was started in the spring of 2011 at the Domaine de Lamothe – INP-EI Purpan, Seysses, Garonne Plain, south-western France (43.506 N, 1.237 E). The soil was classified as a stagnic Luvisol according to the World Reference Base for Soil Resources (IUSS Working Group WRB, 2007), with an illuvial clay horizon between 35 and 60 cm. The substratum was an alluvial pebbly layer at around 150 cm. Averaged soil texture in the arable layer (0-30 cm) was 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 and details of soil composition for each experimental plot are given in Table II.1. Each sample, coming from 5 subsamples pooled together, was characterized by its particle size distribution (% weight) after removal of the organic matter by H_2O_2 and decarbonatation by HCl (Association Française de Normalisation [AFNOR], 1983), its organic carbon content (g kg^{-1}) by sulfochromic oxidation (AFNOR, 1999a), its pH in water, its Ca content (g kg^{-1}) by the volumetric method (AFNOR, 1999b), its K content (g kg^{-1}) by the ammonium acetate method (AFNOR 1992) and its P_2O_5 content (ppm) by the Olsen method with sodium bicarbonate (AFNOR, 1995). All these characterizations were performed by the INRA Laboratory (Arras, France).

Cropping system	Number of plots	Clay (<0.002 mm) (g kg^{-1})	Silt (0.002-0.05 mm) (g kg^{-1})	Sand (0.05-2 mm) (g kg^{-1})	Organic matter (g kg^{-1})	pH	P_2O_5 (ppm)	Ca (g kg^{-1})	K (g kg^{-1})
MM_{Conv}	2	317±42	405±33	280±75	18.4±0.2	6.2±0.3	25.0	4.3	18.6
MM_{LI}	2	300±106	407±83	295±190	17.8±2.3	6.4±1.2	29.0	4.6	19.3
MM_{CT}	2	332±69	429±32	241±100	19.7±0.6	6.8±0.3	17.0	4.1	17.1
Maize-MSW	6	364±83	426±31	209±91	19.1±2.1	7.1±0.6	21.2	4.6	18.6

Table II.1: Main characteristics of the topsoil layer (0-30 cm) in each cropping systems treatment.

The climate in the study region is a result of Atlantic, Mediterranean and continental influences, resulting in high rainfall in spring, hot and dry conditions during summer and early autumn, and mild winters. Meteorological data including daily air temperature (°C), rainfall (mm), relative humidity (%), wind speed (m s^{-1}) and direction, were recorded by an automated weather station (SMA100, Campbell Sci., Antony, France) at the experimental site. During the three

years of the experiment (2011, 2012, and 2013), the average annual daily temperature was 13.9°C. The hottest month was August (22.5°C) and the coldest was February (4.9°C) (Figure II.1).

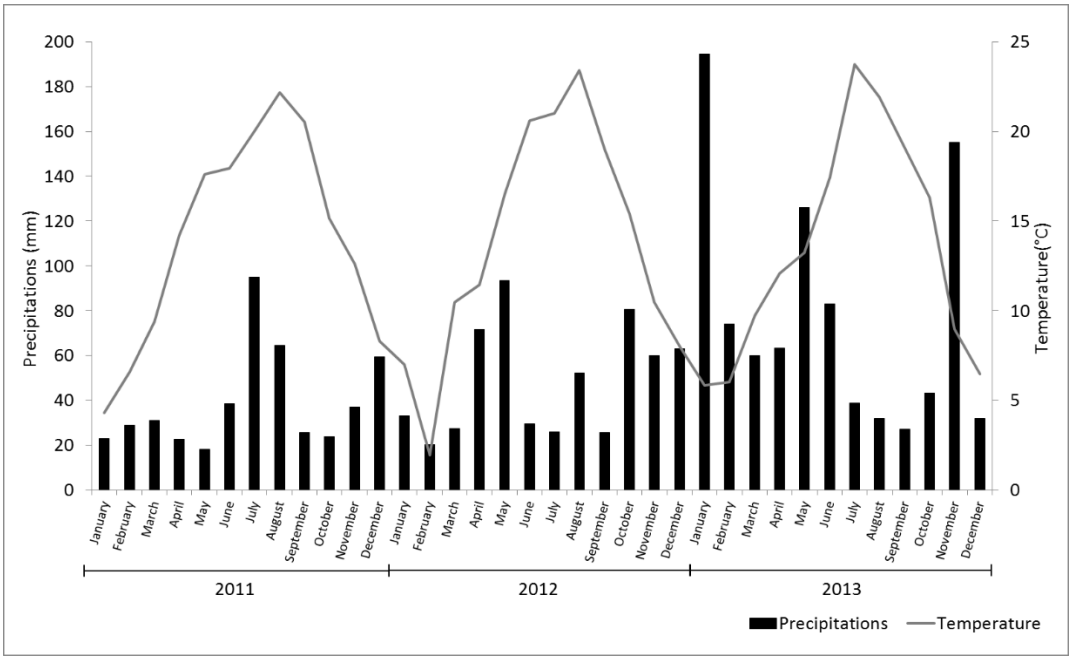


Figure II.1: monthly precipitation and average temperature during the period of the experiment.

2. Cropping systems description

Four MM cropping systems were compared using a holistic approach that aimed at evaluating their agronomic, environmental, and socio-economic performance. The four maize cropping systems differed in their input use intensity and represent a gradient from a high-input conventional monoculture to a low-input integrated cropping system rotation. Main objectives and key points of the management of each cropping system are mentioned below and additional information is given in Figure 2:

1. Conventional Maize Monoculture (MM_{Conv}). This maize production system was designed to maximize the gross margin, according to the conventional system practiced in the South-West of France. In order to avoid water, nitrogen and macronutrients stresses, inputs were not limited and main agricultural operations consisted of a spring mouldboard ploughing and a soil maintained bare during the fallow period in winter. Chemical control of weeds (preventative and curative) was used as commonly practiced for conventional maize production. This system is used as the reference to measure the relative performance of the three LI-CS.
2. Low-Input Maize Monoculture (MM_{LI}). A low pesticides, nitrogen (N) fertilizer and irrigation water monoculture aimed at reducing the use of fertilizer-N by 25%, herbicides by 50% (thanks to substitution with mechanical weeding and localized spraying) and irrigation water by 25 % (using an half early variety). The aim was to avoid water pollution by reducing nitrate and pesticide leaching by 50 and 70%,

respectively. Soil and water protection was reinforced by using a cover crop (*Lolium hybridum + Trifolium* spp.) during the fallow period, buried by ploughing. Finally, this system aimed at maintaining the same gross margin as MM_{Conv}.

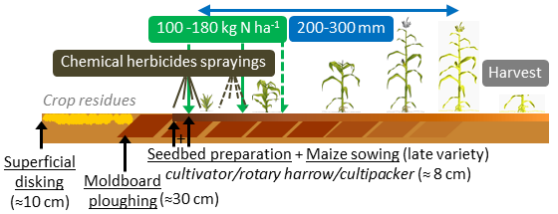
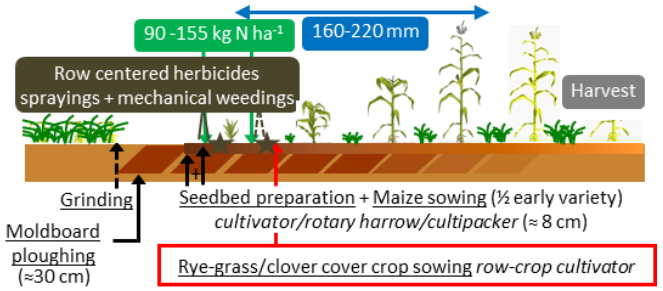
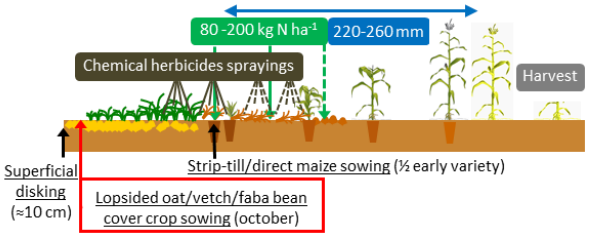
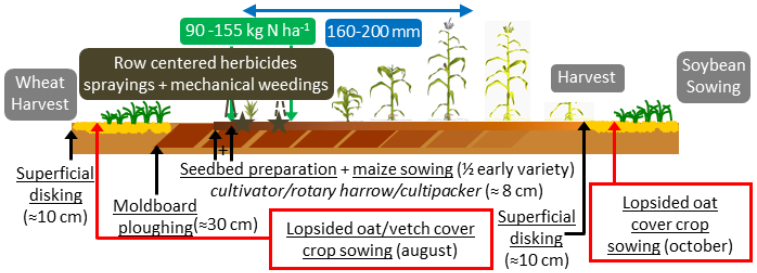
3. Conservation Tillage Maize Monoculture (MM_{CT}). The main objective of this system was to reduce energy consumption and GHG emissions by 40%. The objective was also to reduce pesticide leaching by 50%. To reach these objectives, conservation tillage practices were implemented and maize was either sown after strip tillage (2011 and 2012) or directly in no-tillage management (2013) and a cover crop was sown immediately after maize harvest. In this system, weeds were chemically controlled with the objective to maintain the use of herbicides at the same level as MM_{Conv}. A slight gross margin reduction of 10% was accepted in regard to MM_{Conv} as a compensation of human labour reduction.
4. Integrated Maize Rotation (Maize-MSW). This system included a three-year rotation of maize-soybean-winter soft wheat and was designed to reduce, at the rotation level, the inputs of herbicide, irrigation water and fertilizer-N by 50% compared to MM_{Conv}. Results from only the maize phase of the rotation are presented here. The maize prioritized the same input reduction objectives as MM_{LI}, reducing the use of herbicides by 50% and the use of fertilizer-N and irrigation water by 25%. As for MM_{LI}, the objective was to reduce nitrate and pesticide leaching by 50 and 70%, respectively. However, Maize-MSW aimed at maintaining the same gross margin as MM_{Conv}.

For each type of technical act, and especially the ones dealing – directly or indirectly – with IWM (e.g. weeding, choice of cover-crop species), decision-rules were designed for optimum management and for deciding in practice the application of inputs. According to the possibilities allowed on each system (e.g. on MM_{LI}, mechanical weeding, local spraying or chemical weeding) and to the technical information available (e.g. soil moisture, weather, weed pressure), a strategy was established in order to have an optimum management of the system and to reach, as much as possible, the initial objectives. According to the crop and soil status, when the initial objectives proved to be incompatible with a necessary operation for a correct management of the crop, the former took priority.

The irrigation was realized with a frontal irrigation sprinkler system and was managed as following: MM_{Conv} irrigation aimed at satisfying 100% of the maximum evapotranspiration (MET) whereas a slight stress was accepted on the three LI-CS with the objective of satisfying 90% of the MET. The triggering of the irrigations was then decided according to the 20-cm and 50-cm depth matric potential and water content values (measured with tensiometers and Thetaprobes). To decide the amount of fertilizer-N applied, a N balance-sheet method was applied every year on each system, taking into account the N inputs (mainly cover crop and residues restitution, annual mineralization, residual mineral N at harvest) and the N outputs (mainly objective grain yield, residual mineral N at harvest, eventual immobilization by cover crops or residues). Afterwards, the N fertilization was decided in order to full-in all the crop needs except in 2013 were the rainy weather impeded the usual two applications of fertilizer-N.

The varieties were also chosen according to the objectives of the systems. For MM_{Conv}, a late maize variety was chosen to valorise the longest the growing season and increase yield whereas

on the three LI-CS, a shorter cycle variety was used in order to reduce the input needs (irrigation and N fertilization) and to maximize the development of the cover crops during autumn.
Within the constraints chosen for each cropping systems (e.g. no-till for MM_{CT}), an optimal agronomic and economic management was privileged. Every year, different trade-offs in terms of input uses or technical operations were determined, as presented in Figure II.2 and fully described on the Supplementary Material 1.

System	Agronomic	Economic	Environmental	Social	Technical management
MM_{Conv}	- Reinforced protection against weeds and pests to avoid stresses for the crop - Irrigation : satisfaction of 100% of MET - Mineral N : satisfaction of 100% of the needs - Optimum seedbed for a good implanting	Optimize the gross margin	-	-	
MM_{LI}	- Irrigation : satisfaction of 90% of MET - Mineral N : satisfaction of 100% of the needs - Weeds tolerated when not numerous and with a shift stage compared to the crop - Optimum seedbed for a good implanting	Equivalent gross margin than MM_{Conv}	- ↘ by 50% HTFI and pesticides leaching in the surface water - ↘ by 25% the use of mineral-N fertiliser and by 70% $N0_3^-$ leaching - ↘ by 25% the use of irrigation water - ↗ the carbon content of the soil - ↘ by 20% energy use	- Limit at the maximum the occurrences of contact between applicator and pesticides - Limiting by 10% the raising of the working time	
MM_{CT}	- Irrigation : satisfaction of 90% of MET - Mineral N : satisfaction of 100% of the needs - Weeds tolerated when not numerous and with a shift stage compared to the crop	90% of MM_{Conv} gross margin	- ↘ by 50% the use of fuel - Equivalent HTFI - ↘ by 50% pesticides leaching in the surface water - ↘ by 15% use of mineral-N fertiliser and by 50% $N0_3^-$ leaching - ↗ the carbon content of the soil and the soil microbial activity - ↘ by 40% energy use	↘ by 50% the working time	
Maize-MSW	- Irrigation : satisfaction of 90% of MET - Mineral N : satisfaction of 100% of the needs - Weeds tolerated when not numerous and with a shift stage compared to the crop - Optimum seedbed for a good implanting	- Equivalent gross margin than MM_{Conv} - Diversify the crop productions (at farm scale level)	- ↘ by 50% the HTFI and pesticides leaching in the surface water - ↘ by 25% the use of mineral-N fertiliser and by 70% $N0_3^-$ leaching - ↘ by 25% the use of irrigation water - ↘ by 25% energy use	- ↘ working peaks (at farm scale level) - Limit at the maximum the occurrences of contact between applicator and pesticides	

With N-fertilization dose; Irrigation dose; ★ mechanical weeding operation; /\ /\ chemical herbicide spraying/centered on the row; operations not systemically done are drown dotted.

Figure II.2: Main characteristics of the cropping systems tested: agronomic, economic, environmental and social objectives and the main technical management operations.

3. Experimental design

The four systems were compared using 720 m^2 field plots (12 x 60 m). For MSW, each component of the rotation was present every year. Each system and each crop of MSW were randomized in two independent complete blocks. Both plots of each system were managed identically, with, for each system, technical operations made the same day with an identical amount of input. For a more accurate description of the field experiment, see Alletto et al. (2015).

4. Crop and plant sampling

a) Crop season

A crop season, which was called "year", of a system, included the crop of that given year and the following cover crop until its destruction.

Crop, weed, and cover crop measurements

Each plot was divided in two equal sample replication zones (360 m^2 each). On each subplot, the following measurements were made:

- Weed density (plants m^{-2}): Weeds were identified by species and the plants were counted at the 6-8 leaf stage and flowering stage of the maize in five separate 1 m^2 quadrats (1.60 x 0.63 m) placed transversally with the crop rows in order to include two crop rows. The position of the quadrats was fixed throughout the years so all sequential samplings occurred in the same area. In 2013, data from the 6-8 leaf stage was not collected due to excess water and flooding in most of the plots.
- Weed, crop, and cover crop above-ground biomass: at maize flowering and maturity, on 1 m^2 quadrats (1.60 x 0.63 m), the aerial part of crop and weeds were collected, identified, separated into species and dried in an oven for 48h at 80°C and weighted. The date of the measurement was chosen when more than 50% of the plots of the entire trial had reached the target stage (flowering or maturity). At cover crop destruction, on 1 m^2 quadrats (1.00 x 1.00 m), the aerial part of cover crop was collected, dried in an oven for 48h at 80°C and weighed. If the dried biomass of a species (crop, cover crop or weeds) was above 5 g m^{-2}, it was ground separately at 0.1 µm and a 100 µg sample was analysed for its N content with the Dumas method (flash combustion with automatic N analyser, including nitrate) using a Flash 4000 (Thermo Fisher Scientific, Waltham, MA, USA). These data were used to calculate the Nitrogen Nutrition Index (NNI) of the maize and to estimate the amount of N trapped by the weeds. At maturity, crop grain and vegetative part were weighed and analysed separately.
- Crop grain yield: A 10 m^2 uniform centre zone of each subplot (two maize rows, 6.25 m long), was harvested to measure grain yield and grain moisture content. Grain yields presented in the article correspond to the normal sale value of 15%.

The soil data were collected at the plot scale (i.e. the same value for both the subplots). Soil texture was recorded at the beginning of the experiment with one sample per plot, coming from 5 subsamples on the 0-30 cm layer. The residual mineral N in the soil (NO_3^- and NH_4^+) was measured on the 0-30, 30-60, 60-90 and 90-120 cm layers. For each plot, 5 samples were collected and mixed at maize sowing and harvest. Residual mineral N was extracted with 1 M KCl. Nitrate and ammonium concentrations were determined by continuous flow colorimetry (Skalar Analytical). Nitrate ions were reduced to nitrite on a cadmium column and detected by the Griess-Ilosvay method (Henriksen and Selmer-Olsen, 1970) whereas ammonium ions were detected by the indophenol method (Verdouw, 1977) and analysed at 540 nm.
Finally, technical operation data was collected only at the system scale, with a single value for both the plots of a given system.

Herbicide Treatment Frequency Index

TFI (Treatment Frequency Index) is a common yearly indicator used in Europe to measure the yearly pesticide pressure on a plot by using the following formula (Lechenet et al., 2014):

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

where T = a given treatment and Approved dose, the effective application rate of the given T pesticide on a crop for given targeted organisms (Pingault, 2007). The metaldehyde-based molluscicides and the seed treatments, employed in the experiment, are not included in this index since no authorized rates exist for these products. Since they were the only non-herbicides chemicals used on the experiment, the TFI calculated is thus referred as HTFI (Herbicide Treatment Frequency Index) in the article. All the details (treatment area, dates of applications, names and rates of the molecules) of the treatments are specified on Supplementary Material 1.

Nitrogen parameters

N supply for the crop in each cropping system was evaluated (Huggins and Pan, 2003; Dawson et al., 2008). It was calculated by adding, the residual content, in kg ha^{-1} in the 0-120 cm layer of soil, of inorganic N at sowing and the amount, in kg ha^{-1}, of fertilizer-N applied to the crop during the cropping season:

$$\boldsymbol{N\ supply = residual\ soil\ N + applied\ N} \qquad [2]$$

In addition to N supply, the Nitrogen Use Efficiency (NUE) was calculated with the following formula:

$$\boldsymbol{NUE = \frac{grain\ yield}{N\ supply}} \qquad [3]$$

with grain yield and N supply in kg ha^{-1}. This NUE thus represents the overall efficiency of the system since it does not separate the soil and plant influences (Dawson et al., 2008). To evaluate the Nitrogen nutrition status of the crop in vegetation, NNI (Nitrogen Nutrition Index) was also measured at flowering according to the formula proposed in the literature (Plénet and Lemaire, 2000; Ziadi et al., 2008):

$$\boldsymbol{NNI = \frac{\%\ shoot\ N}{\%\ critical\ N}} \qquad [4]$$

with % shoot N the percentage of N in the shoot biomass of the plant and % critical N, defined by Plénet and Lemaire (2000), as "the minimum %N in shoots required to produce the maximum aerial biomass at a given time" and estimated as follows:

$$\%\ \boldsymbol{critical\ N} = \mathbf{3.40} \times \boldsymbol{dry\ matter\ shoot\ biomass}^{-\mathbf{0.37}} \quad [5]$$

A NNI value of 1 indicates that the crop is optimally N balanced while values above 1 indicate an N excess, and below 1, an N deficiency (Ziadi et al., 2008).

b) Socio-economic and environmental data

Gross margin

The variable costs of a cropping system in a given year are the sum of the costs of pesticides and adjuvants, fertilizers, and seeds for both crop and cover crop. Fuel and energy costs were estimated for each management operation (Supplementary Material 2), excluding irrigation since the irrigation material was specific to the experiment and cannot be extrapolated to other situations. Due to the on-station system scale approach, fuel consumption for transport from farm to field as well as the fixed costs were excluded.

Gross income, an easily understandable and interpreted static, was calculated by multiplying the maize grain harvested at standard moisture content by its price. The prices were estimated as the average price in the harvest month at the Chicago commodity market, consulted on the French national statistical institute (INSEE – Institut National de la Statistique et des Etudes Economiques) (Bechini and Castoldi, 2009). Then, the average exchange rate USD-€ in the harvest month, given by on INSEE, was used to convert the commodity price into €. The cost of each input and the economic coefficients of each technical operation are described on Supplementary Material 2.

Labour

Labour use, calculated per hectare every year on each system, was the sum, for each technical operation, of the average speed multiplied by the width of the tool/machinery. By this way, it did not take into account the small size of the plot. Irrigation, managed with an automatic system, was not taken into account. Maintenance of the tools was not taken into account, being relatively little and not adapted a cropping system evaluation. This index slightly overestimates labour use compared to commercial farm data due to the small size of most of the machinery used on the experimental plots. This difference was however taken into account when the objectives were assigned to the cropping system.

Cumulative drainage and number of pesticides leaching events

Water drainage and pesticide leaching were monitored on each plot using tension plate lysimeters (SIC300, UMS GmbH, Munchen, Germany) installed at 100 cm-depth. The diameter of the plate was 31 cm and the tension fixed in the plate lysimeter was -100 cm. A vacuum pump was used to periodically suck out the water accumulated by the plate lysimeter. Leachate samples were kept at 4ºC until analysis. The number of drainage events per year varied during the 3 years of the experiment from 5 to 10 on each cropping system. Leachates were collected during the maize growing season and the beginning of the fallow period (generally until

December). All the compounds applied on the plots (including molluscicides and seed coating) were analysed. In this article, two indicators were used to compare the drainage and pesticide leaching of the cropping systems: the cumulative drainage per year (expressed in mm) and the number of pesticide leaching events with at least one compound (mother compound or metabolite) quantified at a concentration ≥ 0.1 µg L^{-1} (corresponding to the limit for drinking water).

Energy use and greenhouse gas emissions

Energy use and greenhouse gas emissions were estimated using crop yield and input levels for the four cropping systems each year. Primary (e.g., fuel for machinery operations) and secondary (e.g., production and transportation of inputs) sources were estimated with the Farm Energy Analysis Tool (FEAT) (Camargo et al., 2013). Energy use was calculated by multiplying each input rate by its respective energy parameter from the FEAT database (Supplementary Material 2). Default database parameter values that represent the energy required to produce maize inputs were used. Transportation of inputs (i.e. energy required to transfer inputs from manufacturing facilities to the farm) and on-farm fuel needed for maize production were also included in the analysis. The analysis did not include energy use associated with cover crops, electricity, human labour, energy embodied in machinery or other components that contribute relatively small amounts of energy to the overall budget.

GHG emissions were estimated with a similar approach (Supplementary Material 2). Additional GHGs, such as CH_4 and N_2O were converted to kg CO_2e on the basis of their 100-year global warming potentials (GWPs). The Intergovernmental Panel on Climate Change (IPCC) Tier 1 was used to account for direct (i.e. on-site) and indirect (i.e. off-site) N_2O emissions. Indirect emissions included N_2O from N that was transported via volatilization, leaching, and runoff. A default direct emissions value of 1% was used, meaning that 1% of the N added to the system as synthetic fertilizer or crop residue was assumed to be converted to N_2O. For additional details on GHG emission calculations, see Camargo et al. 2013.

5. Achievements of the objectives

To discuss the achievement of the different objectives of the systems, the "percentage of achievement" of the objectives was calculated. This percentage, for each system "j", MM_{LI}, MM_{CT} or Maize-MSW ; according to a variable k, was calculated as the ratio of i) the % of objective, respect to MM_{Conv}, initially assigned to the system j and ii) the quantified level reached on system j divided by the quantified level reached on MM_{Conv}, using the following formula:

$$\%\, achievement_{jk} = \frac{\%\, objective\ assigned_{jk}}{\frac{level_{jk}}{level\ on\ MM_{Conv}}} \qquad [6]$$

For the variables "Yield" and "Gross margin", the inverse formula was used since, for these two variables, an increase is preferable to a decrease.

6. *Statistical analysis*

a) Canonical Discriminant Analysis (CDA)

CDA is a common analysis for cropping system data (Drinkwater et al., 1995; Sosnoskie et al., 2006). It was computed to discriminate the four systems from an agronomic point of view. The 8 variables were chosen to characterize soil differences between the plots and to discriminate the systems in regard of their objectives: the main inputs (herbicides, N and water) and responses to these inputs by the use of indicators (weed number at flowering, weed biomass at maturity, NNI and grain yield) that reflect the health of the crop. To characterize the soil differences, the variable "clay" was retained, as it has a high impact on soil characteristics (e.g. water retention; Gaiser et al., 2000). The CDA was computed with XLSTAT Version 2013.05.09 (Addinsoft, Paris, France) software and its performance was evaluated through the Wilk's lambda value test, based on the maximum likelihood ratio that varies between 0 and 1. A value approaching 0 indicates that the groups analysed are extremely diverse from one another whereas a value of 1 indicates their exact similarity (O'Rourke et al., 2005).

b) Analysis of Variance and mean comparisons test

Mean comparison and Analysis of Variance (ANOVA) were computed with the R statistical core project software, "agricolae" and "car" packages (Fox and Weisberg, 2011; de Mendiburu, 2012). Each variable's homoscedasticity was tested with a Bartlett test, with a *p*-value of 0.01 to reject the null hypothesis. When it was rejected, data were log transformed and the test was computed again. For variables for which the plot is the statistical unit (N=24) – soil and plant measurements – the two replication zones were plot averaged. A linear model was carried out on the entire dataset to identify system, year and interactions effects:

$$Y_{ijk} = \mu + system_i + year_j + system{:}\,year_{ij} + e_{ijk} \qquad [7]$$

For variables for which the system is the statistical unit (N=12), concerning management parameters (e.g. HTFI, labour), the following linear model was calculated:

$$Y_{ijk} = \mu + system_i + year_j + e_{ijk} \qquad [8]$$

For variables with N=24, when the interaction system x year was positive, the dataset was then analysed year by year with the following model:

$$Y_{ik} = \mu + system_i + e_{ik} \qquad [9]$$

Results of each regression were then analysed by an ANOVA. If this was significant ($p < 0.05$) for system and/or for year, Tukey's Honestly Significant Differences (HSDs) were computed for multiple comparisons of means with a *p*-value of 5%. P-values ranging between 0.05 and 0.10 are specified. Linear correlations between quantitative variables were also studied and validated with the same threshold of 5%.

III. Results

1. Discrimination of the four cropping systems

The Canonical Discriminant Analysis (CDA) using 8 measured variables shows a good discrimination of the four maize cropping systems, emphasized by the low Wilk's lambda value (0.10; $p < 0.0001$) (Figure II.3, Table II.2).

Variables	Canonical function 1 correlation coefficients	Canonical function 2 correlation coefficients	Canonical function 3 correlation coefficients
Yield (Mg ha^{-1})	0.026	0.754	-0.450
Weeds number at flowering (plants m^{-2})	0.699	-0.552	0.021
Weeds biomass at maturity (g m^{-2})	0.202	-0.745	0.004
HTFI	0.729	-0.100	0.239
Irrigation water (mm)	0.392	0.655	0.111
N supply (kg ha^{-1})	0.249	0.629	0.258
NNI	-0.093	0.375	-0.583
Clay content on 0-30 cm (%)	-0.289	-0.100	0.563

Table II.2: Coefficients for the three canonical functions for the 8 system variables included in the canonical discriminant analysis

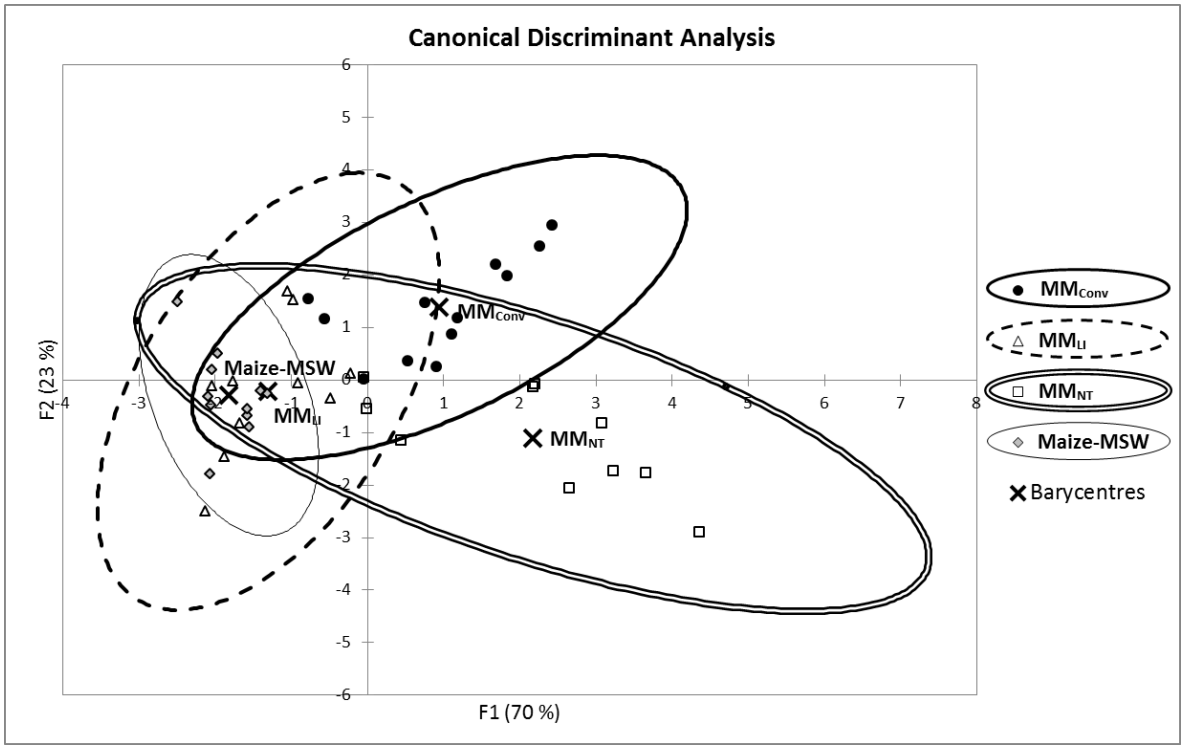


Figure 3: First and second principal components of the Canonical Discriminant Analysis (CDA) derived from 8 variables indicated on the Table 2. The confidences ellipses represent a 5% confidence interval around the data of each system.

The first axis of the CDA (70% of the overall variability) was positively correlated to the HTFI (Herbicide Treatment Frequency Index), making this the main source of discrimination of the maize cropping systems (r = 0.73), and also to weed number at maize flowering (r = 0.70) (Table 2). The second axis (23% of the variability) was positively correlated to the maize yield (r = 0.75) and negatively to the weed biomass at maturity (r = -0.75) then to the weed number at flowering (r = -0.55). It was also positively correlated to two of the main input levels in maize cropping systems, irrigation (r = 0.66) and N supply (r = 0.63), while there was little correlation with the Nitrogen Nutrition Index (NNI; r = 0.37) and almost no correlation with HTFI (r = -0.10). Finally, the third axis is negatively correlated to NNI (r = -0.58) and positively correlated with clay content on 0-30 cm (r = 0.56).

Three groups were visually identified on this CDA: (1) MM_{Conv}, with the highest score on the second axis (barycenter=1.3), indicating high yields with high use of inputs (N and irrigation), it had also a positive score on the first axis indicating above average HTFI and weed infestation ; (2) MM_{CT}, with the highest score on the first axis (high weed pressure – number and biomass – and a high HTFI) while its mean value was negative on the second axis and (3) MM_{LI} and Maize-MSW, grouped together, with reduced use of herbicides, low weed pressure (negative scores along the first axis) and medium yields and use of inputs (scores ranging around 0 on the second axis). According to the size of the confidence ellipses of each cropping system, especially along the first axis that represents most of the variability, MM_{CT} had a low stability of its agronomic performance while maize in rotation (Maize-MSW) had the most stable agronomic performance over the three years.

2. Maize yield

Maize grain yield varied according to the year, the system and their interaction (Table II.3). In 2013, the mean yield was only 8.0±2.4 Mg ha^{-1} while it was significantly higher in 2011 (10.4±1.4 Mg ha^{-1}; $p < 0.05$) and intermediate in 2012 (9.9±2.4 Mg ha^{-1}). Considering the three years of experimentation, MM_{Conv} and MM_{LI}, with mean yields of 11.0±1.1 and 10.3±2.6 Mg ha^{-1} respectively, had significantly higher yields than MM_{CT} (7.8±1.9; $p < 0.05$). It was intermediate for Maize-MSW with 8.6±1.8 Mg ha^{-1}. These differences were smaller at the beginning of the experiment (2011) and increased with time. For MM_{Conv}, maize yield remained stable during the three years of experimentation, whereas it fell in 2013 for MM_{LI} and Maize-MSW.

System	2011	2012	2013	Mean
MM_{Conv}	10.8±0.9	11.3±1.5	11.0±0.9	11.0±1.1a
MM_{LI}	11.5±2.1	11.6±1.4	7.8±2.7	10.3±2.6a
MM_{CT}	10.0±1.1	7.0±0.8	6.3±0.7	7.8±1.9b
Maize-MSW	9.4±0.5	10.0±1.4	6.5±0.9	8.6±1.8ab
Mean	10.4±1.4A	9.9±2.4AB	8.0±2.4B	
p-value (system contrast)	0.60	0.09	0.09	

Table II.3: Grain yield on the four cropping systems for the three years (mean ± SD, letter indicates homogenous group according to a Tukey-HSD test, $p < 0.05$; lowercase letter indicates difference between system and uppercase letter indicates difference between years).

3. Weed abundance and biomass

Weed number at flowering varied from 9±6 weeds m^{-2} (Maize-MSW - early measurement – 2011) to 240±106 weeds m^{-2} (MM_{LI} – early measurement - 2012) (Figure 4-a). Considering the whole dataset, volunteer cover crop species represented less than 1.5% of all weeds (data not shown). The analysis of variance showed a clear effect of the system, the year and the system x year interaction.

In 2011, weed number and biomass were the same for the four cropping systems (Figure II.4), indicating similar initial weed pressure conditions. In 2013, the high rainfall in winter and spring (Figure II.1) led to a higher weed density at flowering (86±115 weeds m^{-2}) than in 2011 and 2012 (45±22 and 53±63 weeds m^{-2}, respectively) ($p < 0.05$).

In 2012 and 2013, MM_{CT} had the highest number of weeds at maize flowering (2012: 150±50 weeds m^{-2}; 2013: 224±163) compared to the 3 other systems (maximum in 2012, Maize-MSW: 24±13 weeds m^{-2}; maximum in 2013, MM_{Conv}: 59±27 weeds m^{-2}) ($p < 0.05$), leading to a significantly higher weed biomass and nitrogen exported by weeds at maize maturity in 2012 (Figure 4). Changes in weed species were also observed in the no-tillage system (MM_{CT}) with a clear development of *Echinochloa crus-galli* and perennial weeds, such as *Convolvulus arvensis*, whereas the conventionally-tilled systems were more invaded by *Polygonum persicaria* and *Kickxia* sp (data not shown).

In 2012, weed density evolution between the early stage of maize development and flowering allowed to evaluate the efficiency of the weed management strategies (Figure 4-a, framed part). The number of weeds at the early stage of maize development was lowest on MM_{Conv} illustrating the efficacy of the preventive chemical weed control on the entire soil surface. On the MM_{CT} system, there were more weeds than on MM_{Conv} despite more herbicide applications. Finally, at this first observation date, MM_{LI} and Maize-MSW also had many weeds due to an absence of weed control prior to the 8-leaf stage of maize. Between the stages 8-leaf and 12-leaf of maize, additional weed control was applied on each system (Supplementary Material 1). On MM_{CT}, no significant change in the number of weeds was found. However, on MM_{LI} and Maize-MSW systems, a strong decrease in weed number was observed illustrating the efficacy of mechanical weed control between the maize rows combined with a chemical weed control on the maize row.

A negative correlation was found between the number of weeds at flowering and the maize yield ($r = -0.46$; $p < 0.01$). This relationship was stronger when only MM_{CT} was considered ($r = -0.76$; $p < 0.01$).

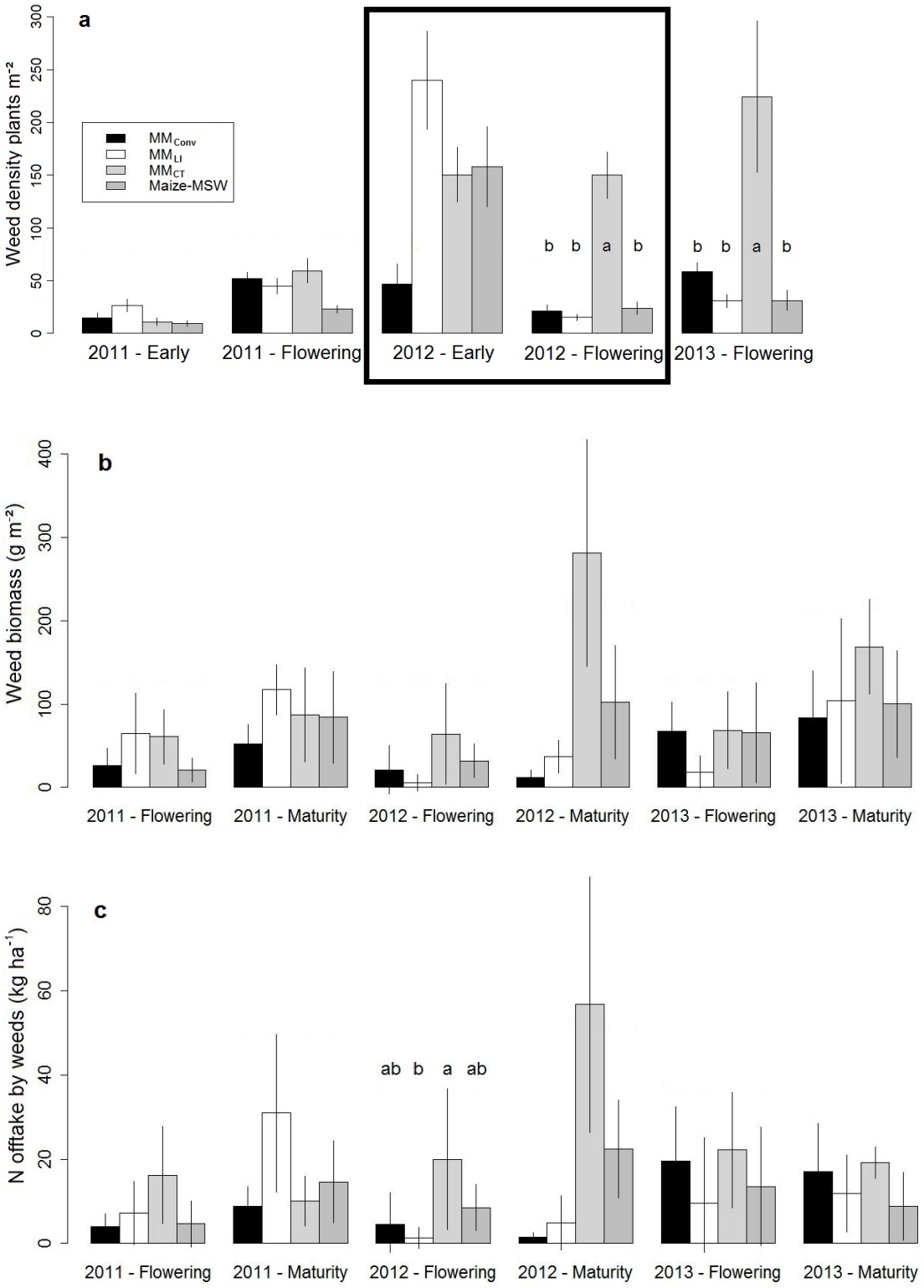


Figure II.4: Weed density (plants m^{-2}) (a), weed biomass (g m^{-2}) (b) and N offtake by weeds (kg N ha^{-1}) (c) in the four cropping systems, from 2011 to 2013. (error bars indicate standard deviation; letters indicate groups according to a Tukey-HSD test at $p < 0.05$)

4. Nitrogen supply and nutrition

Nitrogen supply (Ns) varied during the three years, with high mean values in 2012 (270±37 kg ha^{-1}), intermediate in 2011 (200±42 kg ha^{-1}) and low in 2013 (165±37 kg ha^{-1}) ($p < 0.05$). These differences were due to a higher maize N fertilization (Nf) and higher soil residual mineral N at sowing in 2012 (Table 4). MM_{Conv} Ns (251±50 kg ha^{-1}), composed of soil residual mineral-N at sowing (107±31 kg ha^{-1}) and complementary fertilizer-N (144±36 kg ha^{-1}), was higher than for MM_{CT} ($p = 0.06$), MM_{LI} ($p = 0.06$) and Maize-MSW, ranging from 195 to 205 kg ha^{-1}. MM_{CT}, which kept the cover crop longer in spring, had the lowest soil residual mineral N at sowing (53±41 kg ha^{-1}). At maize harvest, soil residual mineral N differences were smaller.

NNI varied across the three years of the experiment (Table 4). It was high (above or equal to the targeted value of 1.0) in 2011 (1.1±0.2), and in 2012 (1.0±0.1). However, in 2013, the low N fertilization applied to complete the high soil mineral N at maize sowing led to low NNI values (0.8±0.2).

Considering the three years of the experiment, MM_{LI} showed an NNI above 1 (1.1±0.2), higher than MM_{CT} (0.9±0.2) ($p = 0.05$) and Maize-MSW (0.9±0.2) ($p = 0.10$), that had slight N deficiencies with values below 1.0. MM_{Conv} (1.0±0.2) was intermediate but had a high Ns (251±50 kg ha^{-1}).

As a final result, MM_{LI} combined the highest NUE of the four systems (55±14) with lower values of N supply (195±55 kg ha^{-1}) indicating the highest efficiency of fertilizer-N. MM_{CT} system, for which the N supply was medium, reached a lower NUE with 39±21. The NUE reduction on MM_{CT} was particularly significant in 2012 and 2013 (Table II.4).

	System	2011	2012	2013	Mean
N fertilization (kg ha^{-1})	**MM_{Conv}**	160	176	96	144
	MM_{LI}	130	155	87	124
	MM_{CT}	140	205	82	142
	Maize-MSW	130	155	87	144
	Mean	140	173	88	
NUE	**MM_{Conv}**	44±5	37±4ab	54±5	45±8
	MM_{LI}	57±14	46±2a	62±20	55±14
	MM_{CT}	63±12	28±4b	33±18	39±21
	Maize-MSW	53±10	35±3ab	46±10	44±11
	Mean	54±12A	37±7B	50±19AB	
NNI	**MM_{Conv}**	1.2±0.2	1.0±0.1	0.9±0.1	1.0±0.2
	MM_{LI}	1.1±0.1	1.2±0.1	0.9±0.1	1.1±0.2
	MM_{CT}	0.9±0.2	1.1±0.2	0.7±0.1	0.9±0.2
	Maize-MSW	1.1±0.2	1.1±0.1	0.7±0.1	0.9±0.2
	Mean	1.1±0.2	1.0±0.1	0.8±0.2	
Residual mineral N at sowing (kg ha^{-1} on 0-120 cm)	**MM_{Conv}**	88±59	126±16	107±9	107±33
	MM_{LI}	77±17	96±25	40±5	71±29
	MM_{CT}	22±16	34±6	103±39	53±43
	Maize-MSW	53±31	133±65	59±40	82±54
	Mean	60±38	97±50	77±37	
Residual mineral-N at harvest (kg ha^{-1} on 0-120 cm)	**MM_{Conv}**	89±63	111±47	97±22	99±44
	MM_{LI}	79±45	98±25	89±5	89±28
	MM_{CT}	79±10	86±7	87±0	87±6
	Maize-MSW	48±5	110±46	99±14	85±38
	Mean	76±39	101±33	93±13	

Table II.4: Main indicators for nitrogen use for the four cropping systems on the three years. (mean ± SD, letter indicates homogenous group according to a Tukey-HSD test, $p < 0.05$; lowercase letter indicates difference between system and uppercase letter indicates difference between years). For N fertilization, no comparison was computed.

2.1.Herbicide Treatment Frequency Index (HTFI)

On all the cropping systems, the use of herbicide increased with time during the three years of the experiment. This was due to rainy springs in 2012 and 2013 leading to a high weed pressure (Figure 1). Despite this increase, the mean HTFI of MM_{Conv} was 2.06±1.04, which is similar to the average value (2.2) in this maize production region. The two maize systems based on a combined mechanical and chemical weed control, MM_{LI} and Maize-MSW, had the lowest HTFI on average (with values of 1.0±0.8 and 1.1±1.0, respectively) and in every year of the experiment. It reached the objective of a 50% decrease compared to the conventional system (MM_{Conv}) (Table 5). The conservation tillage system, MM_{CT}, had the highest HTFI with an average value of 2.9 and a maximum of 3.5 in 2012.

5. Cover crop production

In all the cases but one in which the cover crop was destroyed before winter, cover crop biomass was above 1 Mg DM ha^{-1}. Biomass production was greater in 2012 (3.6±1.6 Mg DM ha^{-1}) than 2013 (1.9±1.0 Mg DM ha^{-1}) and 2011 (0.9±0.5 Mg DM ha^{-1}), due to heavy winter rainfall, mild winter temperatures and later destruction (Figure 1; Supplementary Material 1) ($p < 0.05$). Early destruction of the cover crops in 2011 led to low biomass even though the seeding date was early. Biomass of the MM_{CT} (2.9±2.0 Mg DM ha^{-1}) cover crop was greater than the Maize-MSW cover crop (1.4±0.8 Mg DM ha^{-1}) ($p < 0.05$) whereas cover crop biomass in the MM_{LI} was intermediate (2.0±1.4 Mg DM ha^{-1}). In both 2012 and 2013, MM_{CT} cover crops which were terminated late (2012: 5.3±1.0 Mg DM ha^{-1}; 2013: 2.4±0.5 Mg DM ha^{-1}) had more biomass than MM_{LI} (2012: 3.4±1.0 Mg DM ha^{-1} ($p = 0.06$); 2013: 1.6±1.4 Mg DM ha^{-1}) and Maize-MSW (2012: 2.1±0.4 Mg DM ha^{-1} ($p < 0.05$); 2013: 1.6±0.7 Mg DM ha^{-1}) despite earlier sowing in those two systems, especially the MM_{LI} where the cover crop was sown as a relay inter-crop, early in the maize crop (Supplementary Material 1).

6. Gross margin

Gross margin varied according to the year ($p < 0.05$), depending on the grain yield and the grain prices: it varied from 290±312 € ha^{-1} in 2013, when yields and commodity prices were low (8.0 Mg ha^{-1} and 127 € Mg^{-1} respectively), to 1603±612 € ha^{-1} in 2012 when both grain yield (9.9 Mg ha^{-1}) and prices (228 € Mg^{-1}) were high (Table 5). The results of 2011 were intermediate in maize price and reached a mean of 1140±261 € ha^{-1}. The gross margin also varied considerably according to the system considered. MM_{Conv} and MM_{LI} had higher margins, typical of what is achieved in the region with 1252±572 and 1254±809 € ha^{-1} respectively, than Maize-MSW (928±722 € ha^{-1}) that is intermediate while MM_{CT} had a significantly reduced margin with 637±458 € ha^{-1} ($p < 0.05$). These results are mainly explained by yield differences between the systems but also by reduced operating costs, which were lower for MM_{LI} and Maize-MSW with 650±91 € ha^{-1} and 673±112 € ha^{-1} respectively, compared to MM_{Conv} (721±37 € ha^{-1}) and MM_{CT} (791±11 € ha^{-1}).

7. Labour

Few differences were observed between years for the workload that was identical in 2012 and 2013 with 7.2 hours ha^{-1}, and slightly less in 2011 with 6.4 hours ha^{-1}. However, differences between systems were substantial, with MM_{CT} having a smaller workload (4.5±0.8 hours ha^{-1}) than MM_{LI} (7.2±0.7 hours ha^{-1}), MM_{Conv} (7.5±1.0 hours ha^{-1}) and Maize-MSW (8.4±1.6 hours ha^{-1}) (Table 5) for which mouldboard ploughing (2.9 hours ha^{-1} on average) is very time consuming. The workload for MM_{Conv} and Maize-MSW increased from 2011 to 2013 due to more numerous weeding operations from year to year (chemical spraying plus, for Maize-MSW, mechanical weeding). MM_{LI} and MM_{CT} workloads fell in 2013 when MM_{LI} was not ploughed and MM_{CT} switched to strict no-till.

8. Cumulative drainage and number of pesticides leaching events

Cumulative drainage during the maize growing season varied from year to year: it was significantly lower ($p < 0.05$) in 2011 (15±17 mm) than in 2012 (65±43 mm) and 2013 (55±30 mm). Although the total amount of water (irrigation + rain) received during the cropping season was similar in 2011 and 2012 (470 and 479 mm respectively), its distribution was different since, in 2012, rain fell mainly in April-May, immediately after maize sowing, while in 2011 it fail mainly in July, when the water demand of the maize is high. Averaged over the three years, MM_{LI} and Maize-MSW showed less drainage than the two other systems. However, differences between systems were most pronounced in 2012, with a higher cumulative drainage on MM_{CT} (119±35 mm) than on MM_{LI} (38±9 mm) or on Maize-MSW (34±19 mm). MM_{Conv} was intermediate with 68±44 mm.

Pesticide leaching also varied according to the year. No pesticide leaching with concentrations > 0.1 µg L^{-1} was observed in 2011, although some pesticides were detected in MM_{Conv} and MM_{CT} (data not shown); whereas, on average for the four systems, 4.6±4.3 events with a pesticide concentration > 0.1 µg L^{-1} $system^{-1}$ were observed in 2012 and 5.5±4.4 in 2013. Differences between systems were notable with Maize-MSW (0.7±1.6) and MM_{LI} (1.8±1.9) recording fewer events than MM_{Conv} (6.5±5.6) and MM_{CT} (4.5±4.3) (Table 5; $p < 0.05$). There were strong system x year interactions since, in 2011, there was no difference between systems and, in 2012, large differences appeared with MM_{CT} that had more events (9.5±0.7) than MM_{LI} (1.5±0.7) and Maize-MSW (0±0). MM_{Conv} (7.5±2.1) was intermediate in 2012 but resulted in the highest number of events in 2013 (12.0±2.8).

9. Calculated energy use and GHG emissions

Analysing each year separately revealed variability in energy use and GHG emissions within maize production systems. Nitrogen fertilizer was the greatest single energy input across all maize production systems, accounting for between 25 and 55% of all energy use depending on year (Figure II.5). Energy use varied from year to year as a result of changes in management and production inputs. In 2 of the 3 years, energy use was approximately 20% greater in MM_{Conv} compared to the other three treatments. However, in 2012, the higher nitrogen and potassium fertilizer application rates led to an increase in energy use in the MM_{LI}, MM_{CT}, and Maize-MSW systems. Energy use from crop drying also varied with the year and system. Grain moisture at maize harvest ranged from 17 to 26%, requiring 800 to 4 300 MJ y^{-1} in energy use from grain drying. The energy used to dry grain when maize was harvested at high moisture contents (e.g. MM_{Conv} in 2013) was almost as much as that from all on-farm diesel fuel use for field operations. When averaged across maize production systems, energy production efficiency was 8.4, 9.1, 6.7, and 7.6 (MJ_{output} MJ_{input}^{-1}) in the $MM_{Conv,}$ MM_{LI}, MM_{CT}, and Maize-MSW systems, respectively.

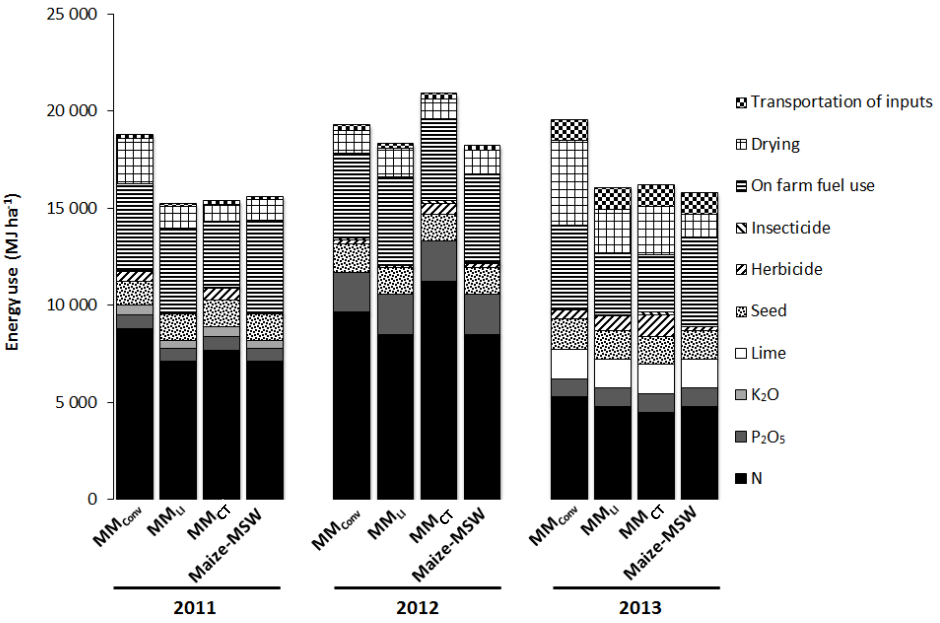


Figure II.5: Components of energy use analysis by year and by system.

Nitrous oxide (N_2O) from synthetic fertilizer was the largest single contributor to the calculated GHG emission across all maize production systems. The GHG emissions associated with the production of nitrogen fertilizer accounted for the second single largest contributor across systems. Similar year-to-year variability was observed in the estimated GHG emissions as for energy use. The Maize-MSW system consistently produced lower GHG emissions than the MM_{Conv} system. The application of lime to increase soil pH accounted for approximately 20% of all emissions, but only in 1 of 3 years that this amendment was applied. When averaged across years, GHG intensity was 18.1, 17.6, 24.9, and 20.2 (g CO_2e per MJoutput) in the MM_{Conv}, MM_{LI}, MM_{CT}, and Maize-MSW systems, respectively.

IV. Discussion

The study aimed to test LI-CSs alternatives to high input (N fertilizer, herbicides, irrigation water and fuel) continuous maize that suffers from many limitations attributed generally to intensive arable farming from a technical point of view with multi-herbicide-resistant weeds (Powles and Yu, 2010), increasing pest pressure [*e.g.* corn borer (Kocmankova et al., 2010)], and, especially, environmental concerns such as soil and water degradation (Konstantinou et al., 2006), and GHG emissions (Millar et al., 2010). Economic concerns are also relevant, due to the variability of the maize price on the world commodity markets (Serra and Gil, 2013). Although technical solutions, [*e.g.* mechanical weeding (Melander et al., 2005), choice of early varieties (Velasco et al., 2004)], provide partial solutions to technical limitations, they do not answer the environmental problems caused by maize monoculture. To respond to these various challenges, a holistic multi-years experimental approach, complementary to factorial, was considered as recommended by Drinkwater (2002). The performance of the cropping systems tested was measured for a wide range of parameters, from technical and agronomical aspects to some economic, social and environmental considerations. These parameters allowed to compare maize crops and following cover crops included in four coherent rule-based cropping systems, a conventional maize monoculture (MM_{Conv}) and three LI-CSs (MM_{LI}, MM_{CT} and Maize-MSW) incorporating many IPM principles that the multivariate analysis (Figure II.3) showed to be distinct from each other during the three first years of their installation. The performance of each system is discussed below and the spider diagram (Figure II.6) presents the relative performance of the three LI-CSs with respect to MM_{Conv}.

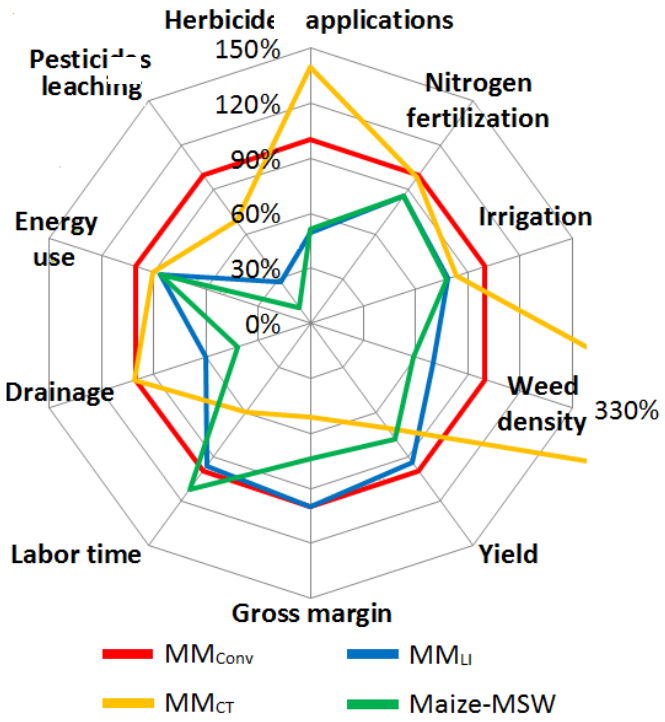


Figure II.6: Spider diagram of the relative performances of the three low-input cropping systems (MM_{CT}, MM_{LI} and Maize-MSW) with respect to the performance of the conventional system (MM_{Conv}) across 10 indicators of sustainability.

1. MM_{Conv}

Conventional maize cropping systems, with deep soil tillage and intensive seedbed preparation, a bare fallow period in winter and non-limiting inputs are dominant in France and widespread in Europe and other regions of the world (Meissle et al., 2009). They result in (i) high yields levels (in our study, from 10.8 to 11.3 Mg ha^{-1}) although higher values can be achieved in more favourable soil and climatic situations (Grassini and Cassman, 2012), and (ii) to procure high gross margins, with a mean of 1252 € ha^{-1} in our study.

In the study, the objectives initially fixed, which were similar to the regional objectives for this conventional system, were all achieved (Table II.5). The % achievements for the uses of inputs were 95% for HTFI (2.1), 85% for nitrogen fertilization (144 kg ha^{-1}), 102% for irrigation water (255 mm) of the initial "regional" objectives. The techno-economic performance was 92% of the grain yield objective (11.0 vs. 12.0 Mg ha^{-1}) and 96% of the gross margin initially set with 1252 € ha^{-1} (Table II.5).

From an environmental point of view, the high post-harvest soil residual mineral N (99 kg ha^{-1} over 0-120 cm), combined with the absence of a cover crop in winter, supports high risks of nitrate leaching (e.g. David et al., 1997). Moreover, the chemical control of weeds allowed a good control of the weed population (Figure II.4) but led to frequent pesticide leaching events (6.5 per year on average) with concentrations above 0.1µg L^{-1}, associated with a high drainage level during the irrigation period of the maize. Finally, this system showed the highest levels of calculated energy use and GHG emissions, essentially due to high levels of N mineral fertilization. These environmental measurements are consistent with the literature (Laabs et al., 2000; Reichenberger et al., 2002; White et al., 2009) and confirm the need to improve the sustainability of this cropping system.

		MM_{Conv}	MM_{LI}	MM_{CT}	Maize-MSW
HTFI	Objective	2.2	50% MM_{Conv}	100% MM_{Conv}	50% MM_{Conv}
	Realized	2.1±1.1ab	1.0±0.8b	2.9±0.8a	1.1±1.0b
	% realized on MM_{Conv}		101%	71%	95%
N fertilization (kg ha^{-1})	Objective	170	75% MM_{Conv}	85% MM_{Conv}	75% MM_{Conv}
	Realized	144±36	124±29	142±52	124±29
	% realized on MM_{Conv}		87%	86%	87%
Irrigation (mm)	Objective	250	75% MM_{Conv}	95% MM_{Conv}	75% MM_{Conv}
	Realized	255±45a	200±30b	212±41ab	198±32b
	% realized on MM_{Conv}		96%	114%	97%
Yield (Mg ha^{-1})	Objective	12	90% MM_{Conv}	80 % MM_{Conv}	90% MM_{Conv}
	Realized	11.0±1.1a	10.3±2.7a	7.8±2.0b	8.6±1.8ab
	% realized on MM_{Conv}		104%	89%	87%
Weed density at flowering (weed m^2)	Objective	/	100% MM_{Conv}	100% MM_{Conv}	100% MM_{Conv}
	Realized	44±20b	31±15b	145±86a	26±10b
	% realized on MM_{Conv}		128%	24%	152%
Gross margin (€ ha^{-1})	Objective	1300	100% MM_{Conv}	85 % MM_{Conv}	100% MM_{Conv}
	Realized	1252±165a	1254±234a	637±138b	928±209ab
	% realized on MM_{Conv}		100%	60%	74%
Labor (h ha^{-1})	Objective	7	110% MM_{Conv}	50% MM_{Conv}	110% MM_{Conv}
	Realized	7.5±1.0ab	7.2±0.7ab	4.5±0.8b	8.4±1.5a
	% realized on MM_{Conv}		115%	83%	98%
Pesticides leaching (number of events)	Objective	/	50% MM_{Conv}	50% MM_{Conv}	50% MM_{Conv}
	Realized	6.5±2.3 a	1.8±0.8b	4.5±1.8a	0.7±0.7b
	% realized on MM_{Conv}		181%	72%	464%
Drainage (mm)	Objective	/	50% MM_{Conv}	100% MM_{Conv}	50% MM_{Conv}
	Realized	59.1±16.2	35.5±8.0	59.5±20.9	24.6±11.3
	% realized on MM_{Conv}		83%	99%	120%
Energy use (MJ ha^{-1})	Objective	/	80% MM_{Conv}	60% MM_{Conv}	80% MM_{Conv}
	Realized	19205±388	16 533±1601	17 493±2974	16 530±1461
	% realized on MM_{Conv}		93%	66%	93%

Reached under 80%
Reached above 80%
Reached above 90%
Reached above 100%

Table II.5: Achievements of the objectives assigned on the main characteristics and inputs of the four cropping systems, in average on the three years.

2. MM_{LI}

The MM_{LI} system achieved its objectives in terms of inputs use at ±15%, taking into account the initial reduction objectives, based on regional data, and the levels recorded on MM_{Conv}. Achievements reached 101% on herbicides with a HTFI of 1.0 corresponding to an initial objective of 50% reduction in respect to MM_{Conv}. Moreover, only 87% of N fertilization (124 kg ha^{-1}, objective of 25% reduction), 96% on irrigation (200 mm, objective of 25% reduction) and 115% of labour (7.2 h ha^{-1}, objective of a maximum 10% increase) were used, indicating the global achievement of the initial objectives (Table II.5).

Despite these input reductions, agronomic performances of MM_{LI} (yield of 10.3 Mg ha^{-1}, equivalent to MM_{Conv}) and gross margin (1254 € ha^{-1} for MM_{LI}, equivalent to MM_{Conv}) remained stable. Indeed, when part of an accurate IPM management strategy, reduction of inputs does not lead to reduced productivity (Archer and Reicosky, 2009; Lechenet et al., 2014) and demonstrates thus an increased inputs efficiency.

Weed control was similar for MM_{LI} and MM_{Conv} (*e.g.* weed biomass at flowering in 2011, 2012 and 2013), due to the efficacy of mechanical weeding eventually completed with localized chemical weeding on the crop row (Mulugeta and Stoltenberg, 1997; Melander et al., 2005). N management with reduced fertilization, that reduced calculated GHG emissions from the system, remained optimum with an NNI of 1.08, equivalent to MM_{Conv} indicating a better efficiency of fertilizer-N applied. The introduction of a cover crop and an earlier variety, consistent with the yield reduction objective, were key features of this management. The variety earliness also allowed the objective of reducing irrigation water to be achieved.

However, this system seems more sensitive to weather conditions since the wet conditions of the spring 2013 did not allow ploughing and efficient seedbed preparation and mechanical weed control (HTFI increase). This emphasizes the interest in having more experimental years for testing this hypothesis according to a wider range of climatic conditions.

From the water quality point of view, the initial impact reduction of 50% compared with the conventional system was exceeded by 81%, with only 1.8 pesticide leaching events on MM_{LI} in comparison to 6.5 events on MM_{Conv}). These results could be explained by the reduction of the total amount applied but also by the cover crop introduction (on average 2.04 Mg ha^{-1} of biomass produced per year) that can improve pesticide sorption and thus reduce leaching (Locke and Bryson, 1997; White et al., 2009; Alletto et al., 2012). The reduction in cumulative drainage was much less well achieved (83%), indicating that effects of annual cover crops on hydric properties of the soil in intensive tillage systems need to be studied over a longer term.

3. MM_{CT}

The adoption of conservation agriculture and of no-till systems in Europe is low (Meissle et al., 2009): reduced tillage, cover crops and direct sowing are used for 15%, 19% and <1% respectively of grain maize acreage in France (Agreste, 2013). Difficulties of weeding or poor emergence could explain this low adoption (Soane et al., 2012). MM_{CT} confidence ellipse size on the CDA (Figure II.3) shows its instability during these three years, in terms of inputs and performance. Although the system reached the objectives for N fertilization and irrigation, it

failed on HTFI which rose by 42%, to 2.94. Only 89% of the targeted yield was reached (7.8 Mg ha^{-1}), which reduced the gross margin (637 € ha^{-1}) that was associated with high variable costs for herbicides. Moreover, the intensive use of herbicides was ineffective for weed control with more than 150 weeds m^{-2} in 2012 and 2013. These weeds took up a substantial amount of N (29 kg N ha^{-1} on average) that affected N availability and nutrition of the crop (NNI=0.86) (Locke and Bryson, 1997).

No-till cropping systems are known to increase weed pressure (Teasdale et al., 1991; Anderson et al., 1998; Swanton et al., 1999; Sosnoskie et al., 2006) and to change the weed community (Anderson et al., 1998; Swanton et al., 1999; Sosnoskie et al., 2006; Trichard et al., 2013). From this study, it can be hypothesized two explanations. The first is that herbicides were inefficient because (i) weeds, due to the curative strategy (as opposed to prevention), were too developed at the treatment date (Holm et al., 2000; Hoss et al., 2003) and/or (ii) the mulch intercepted pre-emergence herbicides and reduced their efficacy (Locke and Bryson, 1997; Chauhan et al., 2012; Cassigneul et al., 2015). The second explanation is that herbicides controlled weeds efficiently but they regrew afterwards due to poor crop development. This would confirm that no-till can limit maize development and yield (Archer et al., 2008; Boomsma et al., 2010), which is not always admitted (Swanton et al., 1999; Cavigelli et al., 2008). An efficient weed management strategy for MM_{CT} is needed, possibly by improving weed control using specific winter cover crops having an effect of weed suppression by soil resources uptake and/or allelopathy (Barnes and Putnam, 1983; Teasdale et al., 1991; Creamer et al., 1996).

Water drainage during the maize growing season was similar for MM_{Conv} and MM_{CT}, despite literature showing higher hydraulic conductivity in reduced tillage systems (Locke and Bryson, 1997). The literature is contradictory on the influence of reduced tillage on pesticide leaching since little influence (Fortin et al., 2002), higher (Locke and Bryson, 1997) and lower (Fermanich and Daniel, 1991; Levanon et al., 1993) leaching under reduced tillage have been recorded. In the experiment, pesticide leaching events were fewer on MM_{CT} (4.5) than on MM_{Conv} (6.5) but did not reach the initial objective to halve pesticide leaching. On a longer term, incorporation of a high biomass cover crop into soil first centimetres every year (2.92 Mg ha^{-1} $year^{-1}$) can enhance pesticides retention and adsorption, as suggested by the literature (Sigua et al., 1993; Locke and Bryson, 1997; Alletto et al., 2010; Alletto et al., 2012).

When the N mineral fertilization reduction was effective (2011 and 2013), calculated energy use fell by approximately 20% compared with MM_{Conv}; 66% of the initial objective was achieved. Strip-tillage and direct sowing reduced labour use to 4.5 h ha^{-1} $year^{-1}$ and reached 83% of the initial objective to halve MM_{Conv} labour (7.5 h ha^{-1} $year^{-1}$). The shift towards direct sowing will help in fully achieving this objective since, in 2013, workload was only 3.8 h ha^{-1} on MM_{CT} as compared to 8.5 h ha^{-1} on MM_{Conv}.

4. Maize-MSW

Crop rotation may have benefited to performance and input parameters of Maize-MSW, stable between 2011 and 2013 (as shown by the small size of the confidence ellipse, Figure II.3).
Herbicide treatments, N fertilization and irrigation were similar between MM_{LI} and Maize-MSW (HTFI=1.09, N fertilization=124 kg ha^{-1} and Irrigation=198 mm). Weed pressure was stable and low (26 weeds m^{-2} at flowering), less than for MM_{Conv} (44 weeds m^{-2} at flowering), which is in accordance with the literature on crop rotation (Sosnoskie et al., 2006).
Although crop rotation is often associated with positive effects on maize yield (Peterson et al., 1991; Wilhelm and Wortmann, 2004), in our conditions Maize-MSW yield was lower than on MM_{LI}: 8.6 Mg ha^{-1} versus 10.3 Mg ha^{-1}. Hence, the gross margin obtained from this system (930 € ha^{-1}) was lower than on MM_{LI} and MM_{Conv}. This result is mainly explained by a very bad yield in 2013 due to specific circumstances (rainy spring and partial flooding on both the Maize-MSW plots).
Due to its small biomass at destruction (1.4 Mg ha^{-1}), it is likely the cover crop provided less N on Maize-MSW than the MM_{LI} cover crop to the following maize, which significantly affected the nutrition status of the crop (NNI=0.9). Moreover, the higher clay content of the soil (36% for Maize-MSW as against 31% for MM_{LI} and 32% for MM_{Conv}) might also affect the performance with the rainy spring of 2013. This element is the most important factor on the third axis of the CDA (Table 2) and is the main one distinguishing this system from MM_{LI}. In the experiment, a negative correlation between yield and clay content of the soil was recorded (r = -0.53, p < 0.01). This soil type might be less favourable for maize development with a slower development in early stages due to low soil temperature (Evers and Parsons, 2003).
However, from an environmental point of view, the Maize-MSW system best satisfied the objectives of impact reduction on cumulative drainage (99%), pesticides leaching (131%) and calculated energy use reduction (93%).

Conclusion

The control MM_{Conv} system tested on the research station produced similar results to the regional means, in terms of input levels (N, irrigation water and herbicides), agronomic performance (weed infestation and grain yield) and socio-economic results (gross margin and workload). As expected, the experiment demonstrated that this system led to large drainage losses and numerous leaching events with pesticide concentrations above the potability threshold of 0.1 µg L^{-1}, inducing high risks for the environment.

The MM_{LI} system, that proposes to maintain monoculture with an IPM approach, gave very similar agronomic, economic and labour results. Moreover, in this system, the use of N fertilizer (-14%), herbicides (-50%) and water (-22%) were reduced, as well as calculated GHG emissions. This management system reduced water drainage and pesticide leaching while probably providing other ecosystem services due to the introduction of a cover crop. Maize-MSW management and results were very similar to those of MM_{LI}, showing the efficiency of the IPM method when introduced into a crop rotation. However, yields were unsatisfactory on one of the three years that indicates that N management and sowing operations can be improved on that system. The experiment is still ongoing in order to check whether technical adjustments made will be effective during the second three-year rotation.

This 3-years transition to no-tillage in the MM_{CT} resulted in poor agronomic and economic performance. Pesticide leaching events were also high, although less than for MM_{Conv}. However, MM_{CT} confirmed some expected benefits, with reduced fuel consumption and labour requirements. Moreover, the incorporation of a high biomass cover crop every year is expected to benefit soil organic matter content and distribution in the top layer as well as improve the long-term agronomic and environmental performances of this system.

In order to rapidly reduce conventional maize monoculture's harmful impacts on water and the environment while maintaining production levels and economic margin, the study proposes, through the MM_{LI} system, a technical and practical solution promising to transfer to farmers.

Acknowledgements

The authors would like to thank all the people who participated in the fieldwork, particularly Mickaël Cazeneuve, Emmanuelle Lherbette, Morgane Froger, Emmanuel Guay, Jean-Marie Savoie, Didier Raffaillac and Jean-Marie Nolot are thanked for their advices on cropping system experimentation and crop cropping and techniques. Marie-Marie Bemer is thanked for the weed data compilation and analysis. This research was financially supported by the ANR Systerra MICMAC-Design project (ANR-09-STRA-06), by the 'Conseil Régional de Midi-Pyrénées' (project n°10051579) and by the ONEMA through the SYSTEM-ECO4 and the ECoPESt projects. The authors would like to thank Alan Scaife for revising the English language.

Chapitre III
Impacts des systèmes de culture alternatifs à la monoculture de maïs conventionnelle sur la dynamique de la flore adventice et influence de la flore adventice sur le rendement



Résumé du chapitre

Contexte

Le chapitre II de la thèse a mis en évidence des performances contrastées des systèmes de culture en fonction des combinaisons de leviers agronomiques employés. Il a notamment été mis en évidence que les systèmes de culture mobilisant la gestion intégrée de la flore adventice obtenaient de bons résultats techniques contrairement au système de culture sans travail du sol. Néanmoins, plusieurs questions de recherche ont été soulevées à la suite de cette étude : i) est-ce que, en cohérence avec la bibliographie sur le sujet, l'augmentation de la flore adventice observée dans le système de culture sans travail du sol est liée également à une évolution de la communauté adventice ? ii) les performances agronomiques mesurées au bout de trois ans sont-elles confirmées après cinq années de mise en place ? et iii) est-ce que les plus faibles rendements observés sur le système de culture sans travail du sol sont dus à la concurrence adventice ou bien peuvent-ils être également expliqués par d'autres facteurs ?

Contenu du chapitre

Ce chapitre porte sur l'étude de la dynamique de la flore adventice d'une monoculture de maïs conventionnelle et de trois systèmes de culture alternatifs mobilisant différentes combinaisons de leviers agronomiques (travail du sol, désherbage, couverture hivernale des sols, fertilisation, choix variétal…). Au-delà de l'approche multicritère globale proposée dans le chapitre II, ce chapitre III permet d'évaluer l'évolution de la flore adventice, bioagresseur de première importance dans les systèmes de culture maïsicoles. Il contribue ainsi à répondre à une question centrale de la thèse concernant la capacité des systèmes de culture alternatifs à gérer les bioagresseurs et l'impact de ceux-ci sur le rendement. Il montre également que les essais systèmes de culture permettent aussi de répondre à des questions plus analytiques et spécifiques qu'une évaluation multicritère globale.

Méthodologie mise en œuvre

La méthodologie mise en œuvre dans cette étude est originale. *i)* Afin de caractériser la flore adventice présente dans les parcelles, *biomasses et abondances des différentes espèces d'adventices ont été mesurées à trois stades phénologiques clés de la culture* : au stade 6-8 feuilles, lors des derniers désherbages de la culture, à floraison et à maturité. ii) *Une mesure du rendement était également réalisée à maturité, au sein des différentes parcelles mais également dans des zones sans adventice* désherbées manuellement tout au long du cycle de la culture et qui avaient ainsi pour objectif d'estimer l'impact de la pression adventice sur le rendement. Cette publication a également permis de contribuer *iii) au développement d'un indicateur « potentiel d'infestation adventice »,* qui est calculé à partir des données d'abondance, sans biais par rapport aux périodes d'émergence de la flore adventice. Il permet ainsi de limiter le risque de surestimer ou sous-estimer la flore présente dans la parcelle du fait de sa répartition en tâches.

Principaux résultats

L'étude a permis de mettre en évidence qu'entre 2011 et 2015 la flore adventice a évolué de manière différente entre les systèmes de culture étudiés. Les principales différences s'expriment

entre le système sans travail du sol et les systèmes labourés régulièrement. Le système sans travail du sol se caractérise par une plus forte présence de graminées estivales et d'espèces vivaces. Cette différence s'exprime dès les premiers stades de développement du maïs, suggérant une efficacité modérée du désherbage dans ce système de culture. Le système de culture en rotation est lui caractérisé par davantage de dicotylédones. L'étude a également permis de révéler que le système de culture sans travail du sol produit des résultats plus variables que les autres systèmes, notamment du fait d'une flore adventice encore en évolution après cinq années d'étude. La faible différence de rendement entre la zone sans adventice et le reste de la parcelle pour tous les systèmes montre que le niveau de flore observé (bien que parfois élevé, dans le cas du système sans travail du sol) n'a que modérément impacté les rendements (<1 t ha^{-1} pour tous les systèmes). Enfin, le plus faible rendement observé dans les zones sans adventices dans le système sans travail du sol montre que les adventices ne sont pas les seules responsables du faible rendement dans ce système.

Apports des résultats pour la thèse

Ce chapitre permet de mieux comprendre comment la flore adventice, principal bioagresseur dans les systèmes de culture maïsicole, évolue sous l'effet de pratiques culturales variées dans le contexte pédoclimatique de l'étude. Cette étude a permis également d'objectiver l'impact modéré de la flore adventice sur le rendement dans le contexte de l'étude. Elle suggère que des facteurs édaphiques rentrent en compte pour expliquer les faibles rendements dans le système sans travail du sol. Les résultats de cette étude ont permis de faire évoluer les pratiques de désherbage du fait de la faible efficacité de certaines pratiques (désherbage mécanique, molécules à action racinaire) dans les systèmes de culture sans travail du sol. Ainsi, les choix de gestion et l'actualisation des règles de décision à la suite des études menées dans les chapitres II et III ont influencé les résultats obtenus dans le chapitre IV qui étudie l'influence des choix de désherbage sous l'angle de l'une de ses principales conséquences environnementales, la pollution des eaux de surface.

Low-input maize-based cropping systems implementing IWM match conventional maize monoculture's productivity and weed control

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cite as: Adeux G, Giuliano S, Cordeau S, Savoie JM, Alletto L, 2017. Low-Input Maize-Based Cropping Systems Implementing IWM Match Conventional Maize Monoculture Productivity and Weed Control. Agriculture 7(9), 74. https://doi.org/10.3390/agriculture7090074

Abstract: 1) Background: conventional Maize Monoculture (MM), a dominant Cropping System (CS) in south-western France, is now questioned for environmental reasons. 2) Methods: three low-input (reduced nitrogen fertilisation, irrigation, pesticide use and/or equipment and labour costs) CS (MM_{LI}, a Low-Input MM implementing ploughing, mixed weeding and cover crops; MM_{CT}, Conservation Tillage MM implementing chemical control and cover crops; Maize-MSW, maize managed like MM_{LI} but rotated with soybean & wheat) were designed to reduce water pollution and were compared to a reference system (MM_{Conv}, a conventional MM resorting to tillage and a high quantity of inputs). Crop production, weed biomass and Potential of Infestation of weeds (PI) of these CS were compared during the first five years after their establishment. Yields were also assessed in weed-free zones hand-weeded weekly in 2014 and 2015. 3) Results: Principal component analysis showed that weed communities did not drastically differ among CS. Weed biomass and PI were higher in MM_{CT}, especially for annual grasses and perennial species. ANCOVA between CS and weed biomass (2011-2015) did not reveal a significant interaction, suggesting that the slope between weed biomass and yield did not depend on CS. Comparison between weedy and weed-free zones (2014-2015) suggested that weeds present at maize maturity affected yields to the same extent for all four CS, despite having different weed biomasses. Grain yields in MM_{Conv} (11.3±1.1 T ha^{-1}) and MM_{LI} (10.6±2.3 T ha^{-1}) were higher than in MM_{CT} (8.2±1.9 T ha^{-1}). 4) Conclusion: These results suggest that MM_{LI} and Maize-MSW are interesting alternatives to conventional MM in terms of weed control and maize productivity.

Keywords: Integrated weed management, cropping system experiment, *Zea mays*, weed competition, weed biomass, conservation tillage, yield loss, *Echinochloa crus-galli*

I. Introduction

Early emerging weeds, such as *Echinochloa crus-galli*, can generate potential grain yield losses of up to 35% in maize (*Zea mays*) (Bosnic *et al.*, 1997). Hence, weed control represents 78% of the total number of pesticide applications in French conventional maize monoculture (Aymard *et al.*, 2014). The massive use of herbicides favours weed resistance (Heap, 2014) and generates water pollution especially when paired with irrigation and high nitrogen (N) fertilisation (Stoate *et al.*, 2001). Conventional irrigated maize monoculture is a dominant cropping system in south-western France (Aymard *et al.*, 2014). Maize monoculture has high yields and financial returns but European and French authorities, through the EU Water Directive (2000/60/EC) and the national Ecophyto plan, respectively, encourage farmers to update their farming practices in order to reconcile environmental and economic performances. Consequently, 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 matches the effectiveness of herbicides, IWM seeks to integrate the effects of many "little hammers", i.e. weed management tools, which have to be organised in a coherent manner in order to design less herbicide reliant cropping systems (Liebman and Gallandt, 1997). Crop sequence is considered as one of the main IWM tools because crop type is a major filter determining weed communities (Fried *et al.*, 2008). Maize monoculture selects for summer and spring-germinating dicotyledonous species (e.g. *Datura stramonium)* and grasses (e.g. *Echinochloa sp.*, *Setaria pumila*) that respond positively to maize practices (e.g. sowing period, irrigation) and associated weather conditions (e.g. high temperature). In contrast, maize cropped in rotation with winter cereals selects for weed species capable of germinating during a wider time frame (e.g. *Polygonum persicaria*) (Fried *et al.*, 2008). Diversifying the crop sequence with winter and/or dicotyledonous spring cash crops can also lead to a greater weed diversity at the rotation level and reduction of dominant species (Chauvel *et al.*, 2001) but also more complex management.

When considering maize monoculture, herbicides and tillage are two major management filters that determine weed species composition (Booth and Swanton, 2000). Studies indicate that conventionally tilled systems (e.g. ploughed) have proportionally more annual weed species whereas non-inversion tillage favours certain annual grasses and perennials (Zanin *et al.*, 1997) and often results in higher weed pressure and diversity (Murphy *et al.*, 2006).

Cropping systems integrating tillage allow the use of the stale-seedbed technique and in-crop mechanical weeding, which can be as effective as chemical control when properly combined (Riemens *et al.*, 2007). Mixed-weeding combining mechanical weeding and herbicide application (cultivation between rows, banded application of herbicide on rows) can provide commercially acceptable weed control and crop yield (Leblanc *et al.*, 1995). Localized applications of N fertilisers can procure crops a competitive advantage over weeds (Di Tomaso, 1995). Cover crops can also be an effective weed management tool through the effect of

incorporation on subsequent maize growth, surface mulch effects in conservation tillage systems or mechanisms of allelopathy (Teasdale, 1996).

The present study aims to compare weed pressure and maize yields and explore the link between the two in a five-year low-input cropping system experiment which was designed to reduce water pollution and improve cropping systems sustainability (Giuliano *et al.*, 2016). These low-input (reduced nitrogen fertilisation, irrigation, pesticide use and/or labour and equipment costs) cropping systems were assessed for their effectiveness in controlling weeds in maize without compromising crop production. It can be hypothesised that low-input cropping systems implementing IWM should (i) modify the weed community (composition, relative species density), (ii) increase weed pressure early in the season since broadcast application of pre-emergence herbicides was substituted by later inter-row cultivations and (iii) not compromise yields because of efficient weed management. Reduced herbicide, fertilisation and tillage should modify the weed community by, respectively, favouring a more diversified community and/or abundant populations, less nitrophilic weed species, and weed species with life forms adapted to tillage regime. Rotation could also increase weed species diversity, reducing abundance of dominant weed species respect to the MM. Moreover, a lower level of available resources (due to lower nitrogen and water inputs) should intensify weed:crop competition. However, we hypothesize that IWM cropping systems will sustain crop production because inputs were optimized and weeding was sufficiently effective.

II. Materials and Methods

1. Study site

The field experiment was conducted at the Domaine de Lamothe – INP-PURPAN, Seysses, in south-western France (43.506 N, 1.237 E). The site was conventionally cropped with a sunflower (*Helianthus annuus*)/soft-wheat (*Triticum aestivum*) rotation for ten years prior to the establishment of the experiment. Maize crops in the experiment were first sown in spring 2011.

The soil is a stagnic Luvisol (IWG, 2007) with an illuvial clay horizon between 35 and 60 cm. Soil texture in the arable layer was silty-clay-loam (40.9% silt, 33.4% clay, and 19.5% sand). The site is subject to modified Atlantic climate with Mediterranean influences. Annual mean precipitation over the five-year period was relatively low (622 mm) but concentrated in late winter and May, enough to produce waterlogging in spring 2013. 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 are principally mild (February is the coldest month, with a mean temperature of 5.7°C).

2. Cropping systems description and experimental design

The cropping system experiment consisted in comparing three low-input cropping systems (two maize monocultures and a three-year rotation including maize) and a conventional maize monoculture considered as the reference system. In addition to crop sequence, the three low-input cropping systems implemented various strategies to reduce inputs compared to the reference conventional maize monoculture (Giuliano *et al.*, 2016). For each cropping system, a set of decision rules was assigned for optimum management. The low-input cropping systems were designed and assessed to address agro-economic, environmental and social objectives (see (Giuliano *et al.*, 2016) for details). In terms of weed management, each system aimed to minimise the impact of weed flora while respecting the set of objectives and constraints decided *ex ante* by experts, as detailed below. The intensity of herbicide use was quantified with the "Herbicide Treatment Frequency Index" (HTFI), which is a commonly used indicator in Europe to measure the annual herbicide pressure on a plot (OECD, 2001):

$$\boldsymbol{HTFI = \sum_T \frac{(Applied\ dose)_T\ x\ (Treated\ surface\ area)_T}{(Reference\ dose)_T\ x\ Plot\ area}} \quad \textbf{(1)}$$

where T = a given herbicide treatment and the applied dose, the treated surface area (in case of localised treatments) and reference dose of the given T herbicide (commercial product) on a crop for a given targeted organism.

a) Conventional Maize Monoculture (MM_{Conv})

MM_{Conv}, a reference production system practiced across south-western France, was designed to maximise financial returns. Crop stress was avoided by using high amounts 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 seedbed preparation, consisting of combinations of cultivators and rotary harrowing (8 cm deep). The soil remained bare during the fallow period in winter. Weed management depended primarily on broadcast preventive-herbicide spraying, in accordance with conventional practices. A curative spray was performed occasionally depending on the emerged weed flora. On average, during the five years of the experiment, the system had an HTFI of 2.3 and used 240 mm of irrigation water and 160 kg ha^{-1} of mineral N per year.

b) 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% (mainly through the use of cover crops and banded nitrogen applications), HTFI by 50% (mainly through between-row mechanical weeding and on-row band spraying) and irrigation by 25% (mainly through the use of an earlier maturing variety). These objectives were 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 (ryegrass/clover) during the fallow period, which was undersown at the 6-8 leaves stage of maize and buried by ploughing in spring. Economically, MM_{LI} maintained a similar gross margin respect to MM_{Conv}.

c) Conservation Tillage Maize Monoculture (MM_{CT})

The main objective of this system was to reduce energy consumption and greenhouse gas 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 (lopsided oat/vetch – from 2011 to 2013 – or faba bean – since 2014) was sown immediately after maize harvest in order to reduce nitrate and pesticide leaching, increase soil organic matter and suppress weeds. Because of no-till and soil type, weeds were chemically controlled with the objective to maintain the same HTFI as MM_{Conv} but this was not achieved over the 2011-2015 period (mean HTFI was 3.1). Objectives for mineral N and irrigation water use were almost reached with annual means of 155 kg N ha^{-1} and 203 mm, respectively. Compared to MM_{Conv}, a slight decrease in gross margin was accepted (-10%) to consider mechanisation costs.

d) Integrated maize rotation (MSW)

This system was a three-year maize - soybean (*Glycine max*) - soft wheat (MSW) rotation designed to reduce, at the rotation level, herbicide, irrigation and N inputs by 50% compared to those in MM_{Conv}. The Maize of that rotation (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%. Over 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 in the experiment.

Input reduction was prioritized differently across the three alternative cropping systems: herbicides, nitrogen and irrigation in MM_{LI} and MSW and fuel, labour time and equipment costs in MM_{CT}.

The four studied cropping systems were a subset of a more diversified cropping system experiment which was set-up as a completely randomized block design (each crop of MSW was also randomized in each block). Both plots of each system were managed identically and decisions were based on a compromise between the agronomic situations of both plots. Plot size was 720 m² (12 × 60m), large enough to use farm-scale tools for soil tillage and crop management. All farming practices are detailed in Supplementary material 1.

3. Weed sampling

Certain species belonging to the same genus were difficult to distinguish at the seedling stage. Thus, 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* spp. refers to *Chenopodium album* and *Chenopodium polyspermum*.

Weed densities (plants m^{-2}) were measured in fixed quadrats at the 6-8 leaf and flowering stages of maize, using ten 1 m² quadrats (1.60 × 0.63 m) in 2011-2013 and then six 0.25 m² quadrats (1.60 × 0.16 m) in 2014 and 2015. In 2013, weed densities at the 6-8 leaf stage were not measured due to excess water 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. Biomass was collected in two 1 m² quadrats (1.60 × 0.63 m) in 2011-2013 and then in four 0.5 m² quadrats (1.60 × 0.32 m) in 2014 and 2015. Collected weed biomass was then dried 48 h at 80°C and weighed.

4. Indicator of weed-pressure: 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 two sampling dates of a given weed species *i* observed in a given quadrat *j* during one crop season (e.g. at maize 6-8 leaf and flowering stages), which was then averaged over the *n* quadrats of the plot (Cordeau *et al.*, 2015):

$$\mathrm{PI}_i = \frac{1}{n}\sum_{j=1}^{n} d\max(d1, d2) \quad (2)$$

At the community level, PI could then be calculated each year as the sum of all PI_i calculated for each weed species (see Supplementary material 2 for a numerical example of PI

computation). 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 and thus, it is not biased by species time of emergence and 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, 1973).

5. Yield assessment

Four 10-m² zones, consisting of two maize rows of 6.25 m in length, 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 2014 and 2015, weed-free zones were set up in 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 measure a "weed-free yield" that could be compared with the yield in the rest of the plot in order to assess the impact of weeds on maize yield. Yield in each weed-free zone was measured by harvesting a 1 m² (in 2014) or a 6 m² zone (in 2015).

6. Statistical analysis

All weed data was 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. However, only two out of the three replicates were sown with maize twice.

Multivariate analysis was performed to determine if the different cropping systems influenced weed-community composition. Samples were ordered through a Principal Component Analysis (PCA). Analysis was performed on the log10(PI+1) dataset with the package FactoMineR of R software (R Development Core Team, 2011) in order to reduce the influence of dominant species. Species with less than 4 occurrences in the overall dataset were removed from the PCA because they were not considered as representative of particular situations.

The weed biomasses and PI (for each species and at the different stages of maize development) were log10(x+1) transformed to stabilise variances. Means were then back-transformed for charts and tables. For all these response variables, a mixed model was performed with the lme function of the nlme package in the R software (R Development Core Team, 2011) on the overall dataset with system as a fixed factor and bloc nested in year as random factors.

ANOVAs were performed on results of each model. If system 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 (R Development Core Team, 2011). Each variable's homoscedasticity and normality of residuals were 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 rejected, data were analysed with a non-parametric Kruskal-Wallis rank sum test and a post-hoc multiple comparison Kruskal-Wallis test with a Bonferroni correction.

Evolution of PI of every species during the 5 year-experiment in the different cropping systems was determined by the slope of the system:year interaction of a mixed model with correlation structure (since measures were repeated on the same statistical units) with system considered as a fixed factor, year as a continuous fixed factor and block as random factor. Since Maize-MSW was only cropped twice on the same plots for two out of three sets of replicates, too few data were available (4 observations) to calculate these coefficients for this cropping system.

In order to examine if the relationship between weed biomass and yield depended on cropping systems, a mixed model was fitted with system, weed biomass at maize maturity (continuous) and their interaction as fixed factors. Block nested in year was computed as random nominal factors. For this equation, yields were computed as the average of the four zones. In order to examine if hand weeding had the same impact on yield for all cropping systems, a mixed model was fitted with system, hand weeding (yes/no) and their interaction as fixed factors and system nested in block nested in year was used as a random factor.

III. Results

Across all cropping systems and weed surveys in maize, 55 weed species were encountered: 39 annuals and 16 perennials. See Supplementary material 3 for list of all species along with their EPPO codes, biological type, relative PI and frequency. *Echinochloa crus-galli* was by far the dominant weed species in the experiment, representing 56% of total PI. The most abundant annual broadleaf species were *Kickxia* spp. (11%) and *Polygonum* spp. (10%). *Convolvulus arvensis* represented 5% of total PI but 59% of the PI of perennial species.

1. Effect of cropping systems on weed communities

The first two axes of the PCA accounted respectively for 16.9% and 11.5% of the total variance (Fig. III.1a). Three weed species contributed the most to the first axis: Solanum nigrum (14%), Polygonum aviculare (9%) and Avena fatua (9%). Echinochloa crus-galli (22%), Digitaria sanguinalis (14%) and Anagallis arvensis (13%) contributed the most to the second axis. MMConv and Maize-MSW were associated with a low abundance of each weed species and a stable weed community across observations (Fig. III.1b). Observations corresponding to MMLI are scattered, indicating a variable weed community and a higher species diversity across observations. MMCT was associated with a greater presence of D. sanguinalis and E. crus-galli and a high variability across observations.

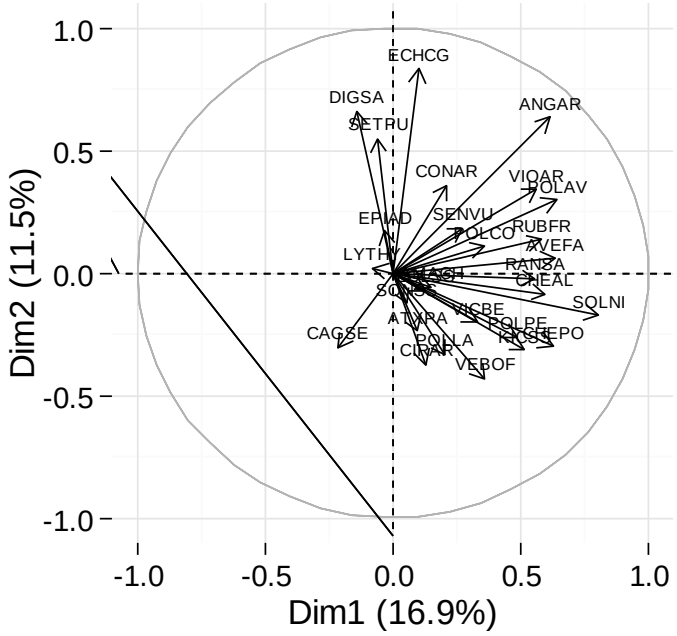


Figure III.1a. Correlation circle with the first two axes of principal component analysis performed for the matrix of plots (four cropping systems) and weed species (described by the "Potential of Infestation" indicator). Weed species are indicated by their EPPO codes (http://eppt.eppo.org).

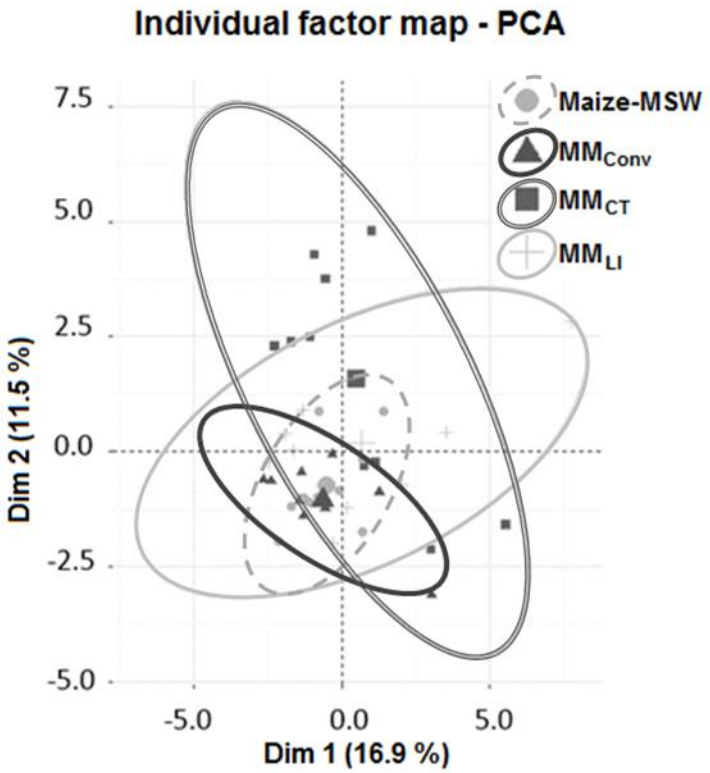


Figure *III*.1b. Scatter diagram with the first two axes of principal component analysis performed for the matrix of plots (four cropping systems) and weed species (described by the "potential of infestation" indicator). Ellipses represent a 95% confidence interval for each cropping system (Maize-MSW: integrated maize rotation; MMConv: conventional maize monoculture; MMCT: conservation tillage maize monoculture; MMLI: low-input maize monoculture).

2. Potential of infestation

Over the five-year experiment, system had a significant effect ($p<0.001$) on mean PI (Fig. III.2). Mean (± standard deviation) PI of MM_{CT} (455±387 plants m^{-2}) was significantly greater than mean PI of MM_{Conv} (49±20 plants m^{-2}), MM_{LI} (86±97 plants m^{-2}) and Maize-MSW (62±63 plants m^{-2}). PI in MM_{Conv} remained low and constant. MM_{LI} also showed a low PI although more variable than $MM_{Conv.}$ MM_{Conv} and MM_{LI} presented similar weed communities with 15-21 % of *E. crus-galli* and 15-22% of *Polygonum* spp. Mean PI in MM_{CT} differed greatly from those in two other MM and was dominated by *E. crus-galli* (80%). Mean PI in Maize-MSW was low and essentially represented by *Kickxia* spp. (41%) and *Polygonum* spp. (22%).

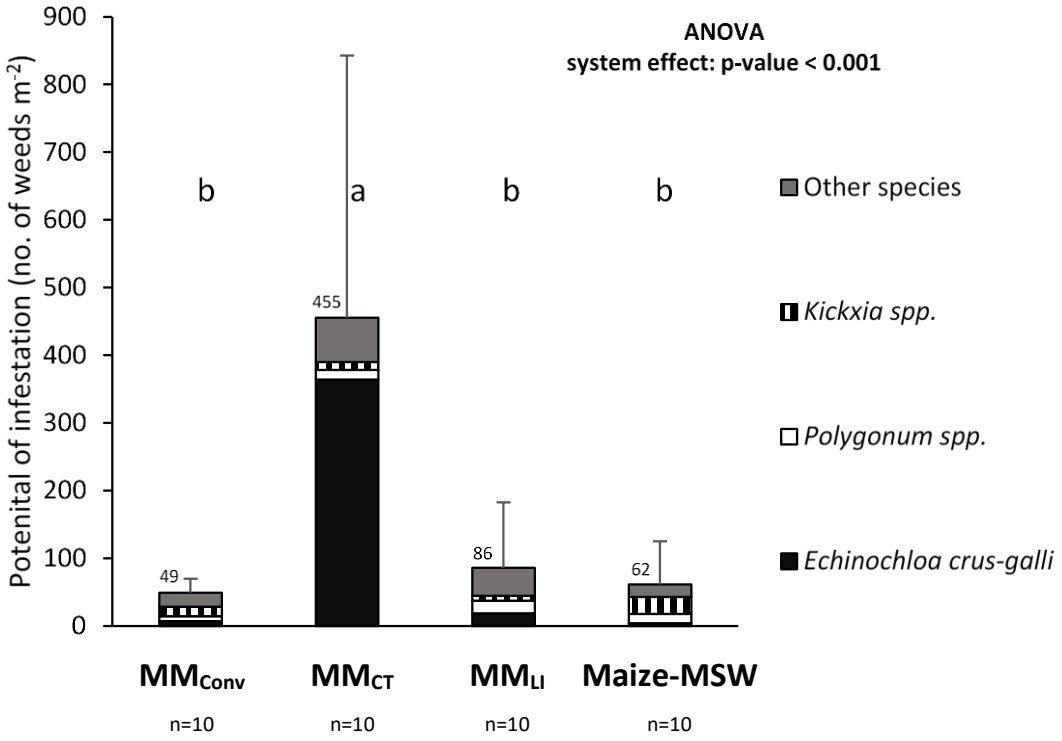


Figure III.2. Potential of infestation (PI, see equation for details) detailed for the three main weed species (mean values over the 5-year period, 2011-2015) in the four cropping systems
(Maize-MSW: integrated maize rotation; MMConv: conventional maize monoculture; MMCT: conservation tillage maize monoculture; MMLI: low-input maize monoculture). Year and block were treated as random factors. Error bars represent standard deviations. Bars sharing the same letter are not significantly different (P < 0.05, Tukey HSD Test).

Significant differences of weed species PI were observed among the cropping systems (Tab. III.1). PI of annual grasses was greater in MM_{CT} (data not shown) than in the reference system mainly because *E. crus-galli* (*p<0.001*) and *D. sanguinalis* (*p<0.01*) were found at greater densities in MM_{CT} (respectively 363±399 plants m^{-2}, 13±29 plants m^{-2}) than in MM_{Conv} (respectively 7±7 plants m^{-2}, 0±0 plants m^{-2}). PI of perennials was also significantly greater in MM_{CT} (data not shown) than in the reference system mainly because PI of *C. arvensis* (*p<0.001*) was greater in MM_{CT} (17±7 plants m^{-2}) than in MM_{Conv} (2±2 plants m^{-2}).

Cropping system	Weed species					
	Convolvulus arvensis+***		*Digitaria sanguinalis*+**		*Echinochloa crus-galli*°***	
MM_{Conv}	2±2	b	0±0	b	7±7	b
MM_{CT}	17±7	a	13±29	a	364±399	a
MM_{LI}	2±2	b	1±1	ab	18±26	ab
Maize-MSW	2±2	b	0±0	b	4±6	b

Table *III.*1. Weed species' potential of infestation (mean±sd, no. of plants m-2) of the four cropping systems (Maize-MSW: integrated maize rotation; MMConv: conventional maize monoculture; MMCT: conservation tillage maize monoculture; MMLI: low-input maize monoculture). For each weed species, mean values followed by the same letter are not different according to Tukey's HSD test (denoted with °) or Kruskal-Wallis test (denoted with +) (** P < 0.01, *** P < 0.001).

3. Weed population dynamics

Mixed models were fitted to determine if PI of weed species in a given cropping system evolved significantly during the experiment. Total PI evolved significantly only in MM_{CT}, increasing from 74±39 plants m^{-2} in 2011 to 1008±203 plants m^{-2} in 2015.

Cropping system	Weed Species			Total
	Convolvulus arvensis	*Digitaria sanguinalis*	*Echinochloa crus-galli*	
MM_{Conv}	-0.37 **	NA	ns	ns
MM_{CT}	ns	0.66*	1.37**	0.66***
MM_{LI}	ns	Ns	ns	ns

Table III.2. Evolution of the potential of infestation (PI, log10 transformed) with time (5 years of experiment) for each weed species in each cropping system (10 observations for each system over the 5-year experiment; MMConv: conventional maize monoculture; MMCT: conservation tillage maize monoculture; MMLI: low-input maize monoculture). Values represent the slope between time and weed species' PI (log10 transformed) in the different cropping systems. Block was treated as a random factor. Slopes were tested to significantly different from zero (* P < 0.05, ** P < 0.01, *** P < 0.001, NA: not applicable, ns: not significant).

Two significant positive evolutions were found with species-by-species analysis in MM_{CT} (Tab. 2): *E. crus-galli* (from 3±1 plants m^{-2} in 2011 to 935±218 plants m^{-2} in 2015) and *D. sanguinalis* (from 0±0 plants m^{-2} in 2011 to 15±18 plants m^{-2} in 2015). One significant negative evolution was found for a species with low PI: *C. arvensis* in MM_{Conv} (from 5±1 plants m^{-2} in 2011 to 0±0 plants m^{-2} in 2015).

4. Weed biomass: effect of cropping systems at different maize growth stages

At the three sampling dates of maize (6-8 leaf, flowering, maturity), weed biomass was greater in MM_{CT} than in the other cropping systems, except Maize-MSW at flowering (Fig. III.3). At maize maturity, mean weed biomass in MM_{LI} (85±50 g DM m^{-2}) was significantly greater than in MM_{Conv} (36±37 g DM m^{-2}). At maturity, Maize-MSW weed biomass (62±39 g DM m^{-2}) was not statistically different from MM_{LI} and MM_{Conv}.

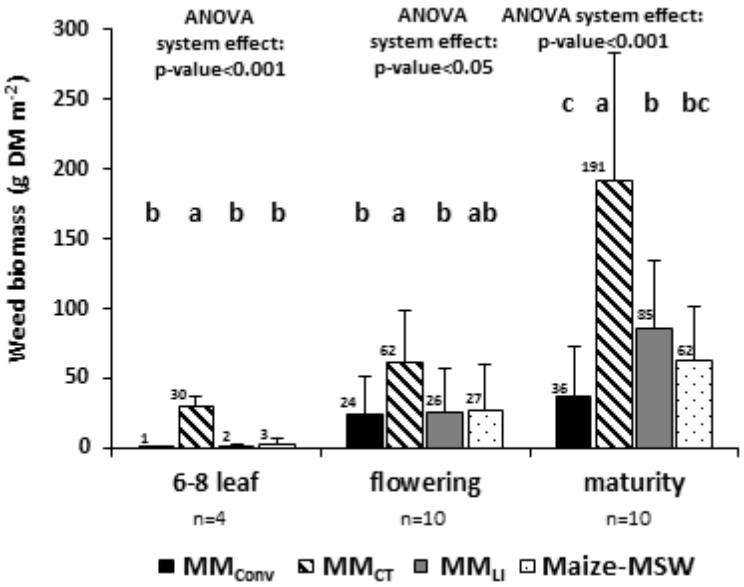


Figure III.3. Mean weed biomass (2011-2015) at three stages of maize growth in the four cropping systems (Maize-MSW: integrated maize rotation; MMConv: conventional maize monoculture; MMCT: conservation tillage maize monoculture; MMLI: low-input maize monoculture). Weed biomass at the 6-8 leaf stage was sampled only in 2014 and 2015. Year and block were treated as random factors. Error bars represent standard deviation. Bars sharing the same letter are not significantly different ($P < 0.05$, Tukey HSD Test). Sampling (days after sowing): 8 leaf (48-58), flowering (76-113), maturity (140-179).

Significant differences in mean weed species biomass were observed among the cropping systems at maize maturity (2011-2015) (Tab. III.3). The total biomass of annual broadleaf species did not differ significantly among the systems (data not shown), but *Polygonum* spp. biomass was greater in Maize-MSW (35±41 g DM m^{-2}) than MM_{Conv} (17±35 g DM m^{-2}) ($p<0.05$). The total biomass of annual grasses was greater in MM_{CT} (data not shown) than MM_{Conv} mainly because *E. crus-galli* ($p<0.001$) had more biomass in this system (140±114 g DM m^{-2}) than in MM_{Conv} (6±7 g DM m^{-2}).

Cropping system	Weed species											
	Chenopodium spp.+*		*Convolvulus arvensis*+**		*Digitaria sanguinalis*+**		*Echinochloa crus-galli*°***		*Polygonum spp.*°*		*Setaria pumila*+*	
MMConv	1±3	ab	1±1	b	0	b	6±7	b	17±35	b	0±0	ab
MMCT	1±3	ab	4±3	a	4±6	a	140±114	a	19±26	ab	3±5	a
MMLI	4±5	a	2±3	ab	1±1	ab	25±29	ab	31±42	ab	0	b
Maize-MSW	0±0	b	2±3	ab	0±0	b	14±21	b	35±41	a	0±0	ab

Table III.3. Biomass of weed species (mean±sd, g DM m-²) between the cropping systems (Maize-MSW: integrated maize rotation; MMConv: conventional maize monoculture; MMCT: conservation tillage maize monoculture; MMLI: low-input maize monoculture) at maize maturity (140-179 days after sowing). For each weed species, mean values followed by the same letter are not different according to Tukey's HSD test (denoted with °) or, when ANOVA assumptions were not met, the Kruskal-Wallis test (denoted with +) (* P < 0.05, ** P < 0.01, *** P < 0.001).

3.5. Impact of weeds and cropping systems on maize yields

Cropping system had a significant effect *(p<0.001)* on maize grain yields. Maize grain yields (Tab. III.4) 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 waterlogging that led 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} (10.9 ± 2.1 T ha^{-1}), which was the only system ploughed that year.

Cropping system	Year					Mean yield	
	2011	2012	2013	2014	2015		
MMConv	10.8 ± 1.1	11.5 ± 1.3	10.9 ± 0.2	11.7 ± 2.2	11.4 ± 1.0	11.3 ± 1.1	a
MMCT	10.0 ± 1.3	6.6 ± 0.8	5.9 ± 0.4	8.5 ± 1.1	9.8 ± 0.4	8.2 ± 1.8	b
MMLI	10.0 ± 1.3	11.5 ± 1.7	7.8 ± 2.8	11.8 ± 2.1	10.3 ± 1.8	10.6 ± 2.3	a
Maize-MSW	9.4 ± 0.6	10.2 ± 1.6	6.4 ± 0.5	10.3 ± 0.1	12.2 ± 0.3	9.7 ± 2.1	ab

Table III.4. Mean maize grain yield (mean±sd, at 15% moisture content, T ha-1) of the cropping systems (Maize-MSW: integrated maize rotation; MMConv: conventional maize monoculture; MMCT: conservation tillage maize monoculture; MMLI: low-input maize monoculture). For each cropping system, mean values followed by the same letter are not different according to Tukey's HSD test (P<0.05).

The analysis between cropping system and weed biomass at maize maturity revealed an effect of cropping system (*p<0.001;* Intercept (T/ha): MM_{Conv} (11.7), MM_{LI} (11.3), MM_{CT} (10.3), Maize-MSW (10.4)) and biomass (*p<0.01;* Slope=-1.1) on yield but did not reveal an

interaction between the two factors *(p=0.29*), indicating that the relationship between weed biomass and yield did not differ among cropping systems.

The analysis of weed free zones revealed a hand weeding (yes/no) effect *(p<0.05)* on yield but no system effect *(p=0.19)* or interaction *(p=0.99)*, indicating that weeds present after management generated similar yield losses among the four cropping systems in 2014 and 2015 (Fig. III.4), despite different weed biomasses. Across all four systems, yields in hand weeded plots (11.6±2.0 T ha^{-1}) were significantly greater than yields in plots without supplemental hand weeding (10.7±1.6 T ha^{-1}).

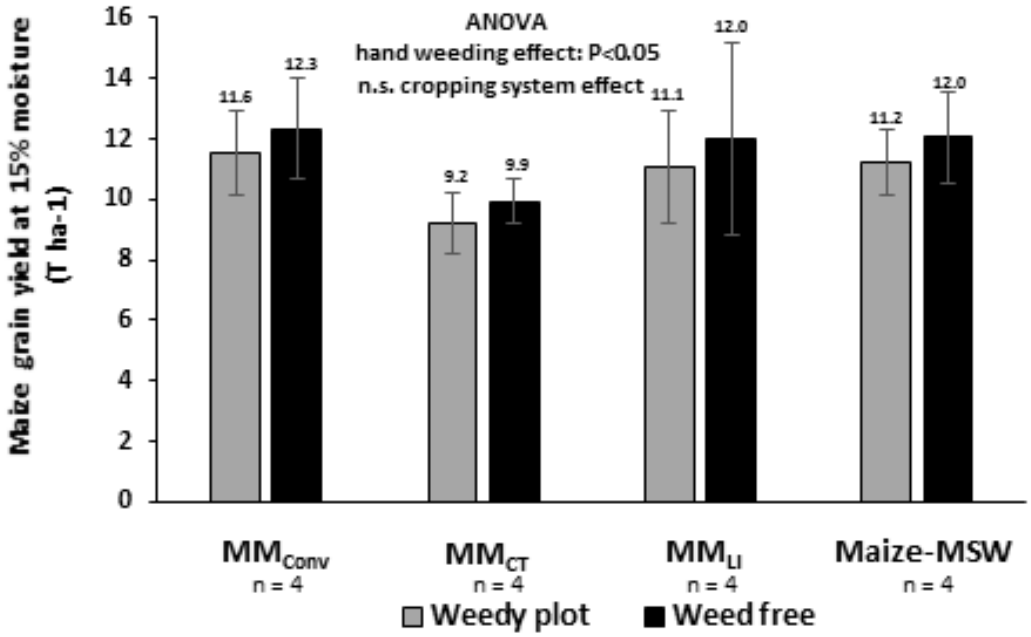


Figure III.4. Mean maize grain yield (at 15% water content, T ha-1) in the presence or absence of weeds (weed-free zones, hand-weeded) assessed in 2014 and 2015 for each cropping system (Maize-MSW: integrated maize rotation; MMConv: conventional maize monoculture; MMCT: conservation tillage maize monoculture; MMLI: low-input maize monoculture). Error bars represent standard deviations.

IV. Discussion

1. Efficient weed management in low-input cropping systems

During this five-year experiment, MM_{Conv} achieved a high and consistent yield and was associated with low weed density and biomass. These results confirm, via a cropping system approach, that the decision rules and resulting weeding and farming practices were sufficient to ensure the economic viability of this cropping system (Giuliano *et al.*, 2016). The combination of farming practices, such as annual mouldboard ploughing (Roger-Estrade *et al.*, 2001), systematic use of pre-emergence herbicides (Pannacci *et al.*, 2007) followed by one or two remedial sprays (Streit *et al.*, 2002), techniques known to be efficient weed-management tools, provided acceptable weed control and achieved high yields. However, this reference cropping system is challenged by the environmental and long-term risks it generates, such as soil erosion due to bare soil during the winter (Stoate *et al.*, 2001), herbicide resistance (Heap, 2014), high pesticide leaching (Alletto *et al.*, 2016) and high greenhouse gas emissions, the former two being confirmed by results collected on that experiment (Giuliano *et al.*, 2016).

MM_{LI} was also a high-yielding cropping system although more variable than MM_{Conv}, based on the standard deviations. PI was also more variable than in the reference system (MM_{Conv}). Differences between these two cropping systems are not as large when one compares weed biomasses – an integrative indicator to measure weed pressure (Primot *et al.*, 2006). MM_{LI}'s weeding strategy (pre-emergence soil-applied herbicides on the row combined with cultivation later in the season) can temporarily lead to high weed density and thus, PI because of the absence of weeding operations in the inter-row early in the season. Yet, weed biomass at maize flowering 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 (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, MM_{Conv} reduced the presence of *C. arvensis*, which is consistent with previous studies (Buhler *et al.*, 1994).

2. 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 transition to conservation tillage, respectively, which illustrates the complicated transition phase often mentioned for these cropping systems (Odihambo *et al.*, 2015) and the importance of implementing rotation as a weed management tool in conservation agriculture (Chauhan *et al.*, 2012). These poor performances can also be the result of an abrupt transition from annual tillage

to no-till without enough time in between for cover crops and organisms to biologically restructure the soil and reorganise soil organic matter (which was low ~2%). Reduced maize yields under conservation tillage have been noted in other studies (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 for the absence of ploughing, mechanical weeding techniques and pre-emergence herbicides, i.e. S-metolachlor, which were abandoned in 2014 in this system because of reduced effectiveness due to surface mulch effect. However, in conservation agriculture, greater herbicide use during the transition phase could be counterbalanced in time by reduced herbicide use (if weeds are well managed and the superficial weed seed bank is depleted), reduced soil erosion, greater carbon sequestration and soil fertility (Chauhan *et al.*, 2012). Higher weed infestation has been observed in conservation tillage agriculture (Buhler *et al.*, 1994) and if weeds are not well managed, like *Echinochloa crus-galli* in MM_{CT} which reached maturity at high densities (see Supplementary materiel 4 for list of species observed with mature or immature seeds at maize maturity in the four cropping systems), they can replenish the weed seedbank and create challenges for weed management over the long term. However, it is not always observed (Murphy *et al.*, 2006) because weed emergence is reduced when seeds remain on the soil surface as in zero-tillage systems (Cordeau *et al.*, 2015). Indeed, under these conditions seed-soil contact is poor and seeds are exposed light (Chauhan and Johnson, 2010).

Along with higher weed pressure, the weed community in MM_{CT} shifted towards annual grasses (*E. crus-galli*, *D. sanguinalis* and *S. pumila*), which completely dominated after the first two years of the experiment, as reported in previous studies (Stoate *et al.*, 2002). 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). *Convolvulus arvensis*, a geophyte perennial broadleaf, most likely benefited from this system due to minimal soil disturbance (Zanin *et al.*, 1997).

3. 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), this 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 high crop performance 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 slightly reduced compared to MM_{LI}, which used a similar strategy to manage the crop, minus crop rotation. Moreover, even though not significantly different, the PI of *E. crus-galli*, the most important weed of the experiment, was 4.5 times lower in Maize-MSW than in MM_{LI}, indicating that rotating maize with winter (e.g. wheat) and/or dicotyledonous (e.g. soybean) cash crops could negatively affect this noxious summer germinating grass species (Chauvel *et al.*, 2001; Kropff *et al.*, 1984). Finally, even though their percentages differed, the main weed species were similar in Maize-MSW, MM_{Conv} and MM_{LI}. It can be hypothesised that, for a given crop type, mouldboard ploughing influences weed composition more than all other techniques used to manage weeds, including crop rotation as suggested by Fried *et al.* (2008).

4. Weed biomass at maturity and maize yield

Even though studies show that the critical period of maize:weed competition extends from sowing to the 3-6 leaf stage (Hugo *et al.*, 2014) or the 3-14 leaf stage (Hall *et al.*, 1992), weed biomass at maize maturity had the highest correlation with maize grain yield. It is most likely that weed biomass at maize maturity integrates the effect of competition between maize and weeds during the entire crop cycle.

More interestingly, the statistical analysis did not reveal significantly different slopes among cropping systems for the effect of weed biomass on maize yield (2011-2015). Since external outputs such as fertilization and irrigation were more important in MM_{Conv}, a reduced impact of weed biomass on maize yields could have been expected in this cropping system.

In contrast, the analysis of weed free zones (2014-2015) showed that weed biomass, even though variable across the cropping systems (at maize maturity: 17±17 g DM m^{-2} in MM_{Conv}, 209±71 g DM m^{-2} in MM_{CT}, 72±54 g DM m^{-2} in MM_{LI} and 24±9 g DM m^{-2} in Maize-MSW), did not significantly affect yields differently across the cropping systems (yield losses varying from 0.7 to 0.9 T ha^{-1}). This suggests that weeds (in 2014 and 2015) were managed as well in the low input cropping systems as in the reference system, mainly because of a delayed emergence with respect to the crop. However, 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). Hence, we can hypothesize that, in this experiment, the influence of soil properties (linked to no-tillage) on maize grain yields was greater than the impact of weed pressure, at least in the context of non-limiting resources. However, it is important to note that maize yields could also have been influenced by other factors that differed among the cropping systems, such as planting date (MM_{CT}), choice of cultivars and fertilization (low-input cropping systems).

Conclusions

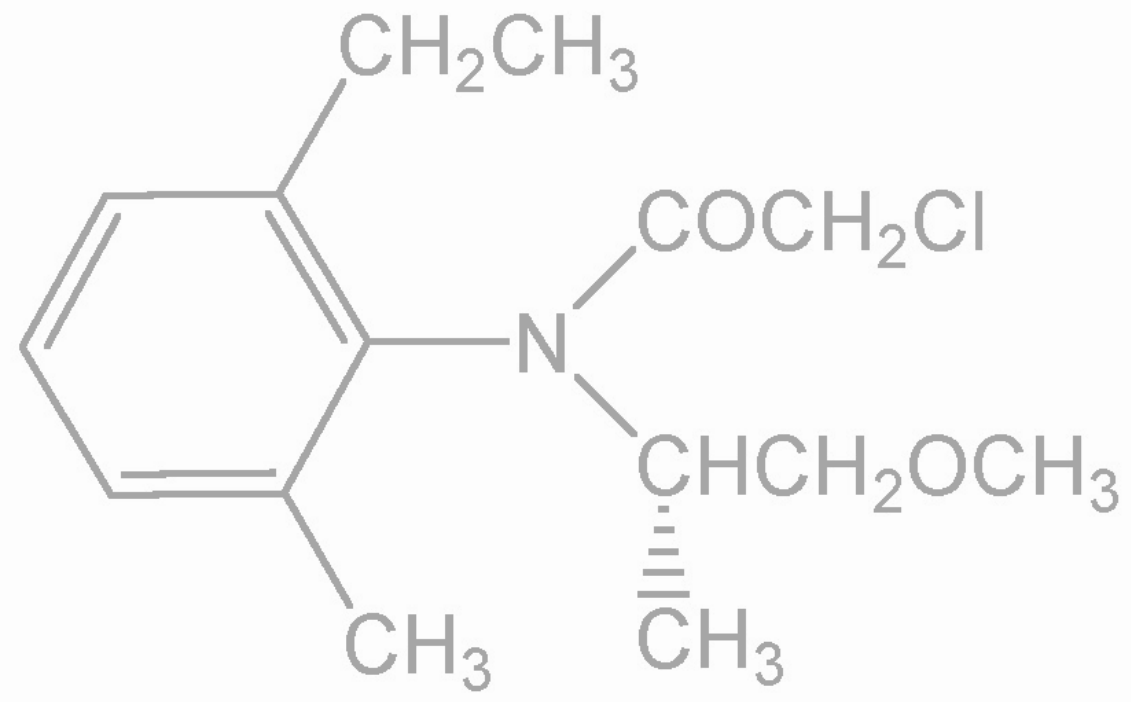
This maize-based cropping system experiment demonstrated that two of three innovative cropping systems which implemented various techniques (such as mechanical weeding, mixed weeding, cover-crop introduction, reduced inputs, and crop rotation) had the same weed management success (in terms of PI and biomass) as the reference system and that weed communities and yields did not drastically differ from the latter, although more variable in MMLI. The overall impact of weeds on maize performance was limited because weeds were well managed, except in the conservation tillage maize monoculture which selected grasses and perennials. 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 and should provide insight on how maize farmers can innovate their cropping systems to maximize environmental benefits without fearing low agronomic performance.

Acknowledgments: They warmly thank François Perdrieux and Gaël Rametti for their involvement throughout the field and laboratory work, Mrs and Mr Corson for their revision of English language and Fabrice Dessaint, Stefano Carlesi and Gionata Bocci for their help with statistical methods. This research was financially supported by the 'Conseil Régional de Midi-Pyrénées' through the ANR Systerra MICMAC-Design project (ANR-09-STRA-06), by ONEMA through the SYSTEM-ECO4 and ECoPESt projects and by the Burgundy Region through the FABER program and CouvHerbi project.

Author Contributions: LA, SG and JMS designed and conceived the experiment. JMS, SG and GA carried out the field work. SC and SG elaborated the research questions. GA analysed the data. GA, SG and SC drafted the article thanks to additional funding from SC. LA was the project leader.

Conflict of Interest: The authors declare no conflict of interest. The founding sponsors had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, and in the decision to publish the results.

Chapitre IV
Impact des systèmes de culture alternatifs à la monoculture de maïs conventionnelle sur l'utilisation des herbicides et la qualité de l'eau



Résumé du chapitre

Contexte

La revue de la littérature (chapitre I) et les expérimentations au champ (chapitres II et III) ont montré que la flore adventice constitue le principal bioagresseur du maïs. En conséquence, les herbicides sont les produits phytosanitaires les plus utilisés dans les systèmes maïsicoles et ceux-ci impactent particulièrement la qualité de l'eau. Néanmoins, peu d'études s'intéressent à la caractérisation des transferts d'herbicide dans l'eau à l'échelle parcellaire, en particulier via le processus de lixiviation. Par ailleurs, la plupart des études existantes se focalisent essentiellement sur une durée restreinte, sur un nombre limité de molécules et comparent, au mieux, différentes modalités de travail du sol. Ces études n'intègrent donc pas les évolutions de la structure du sol au cours du temps ni les interactions entre pratiques agricoles et, en particulier, la nécessaire évolution des pratiques de désherbage (mécanique, localisé, choix des molécules et doses) aux systèmes de culture innovants (réduction du travail du sol, intégration des cultures intermédiaires, décalage des dates de semis).

Contenu du chapitre

Ce chapitre étudie l'impact de différents systèmes de culture maïsicoles sur les eaux de drainage, d'un point de vue quantitatif et qualitatif. Il compare une monoculture de maïs conventionnelle avec quatre systèmes de culture alternatifs mobilisant différentes combinaisons de leviers agronomiques, sur une période de 8 ans qui débute à la mise en place de ces systèmes. Le chapitre considère également d'autres indicateurs technico-économiques et permet ainsi de suivre l'évolution de ceux-ci par rapport aux chapitres II et III.

Méthodologie mise en œuvre

L'étude a pu être menée grâce à *i) la mise en place de plaques lysimétriques* sur l'ensemble des parcelles du dispositif. Grâce à un système de pompes maintenues à dépression équivalente à la capacité au champ, ces plaques ont permis *ii) la collecte des échantillons lors des événements drainants*, hors période hivernale du fait de remontées de nappe phréatique empêchant les suivis. Les collectes de lixiviats avaient lieu régulièrement, après les événements pluvieux principaux et durant la saison d'irrigation. Le volume de chaque lixiviat était ensuite quantifié puis les lixiviats étaient *iii) analysés en laboratoire pour mesurer les concentrations en matières actives herbicides* et leurs principaux métabolites de dégradation. Les données collectées ont été ensuite *iv) analysées via des modèles linéaires en sélectionnant les variables les plus influentes par une procédure Akaike Information Criterion (AIC).*

Principaux résultats

L'étude a révélé que le volume de drainage était le principal facteur expliquant les pertes en herbicides par lixiviation. Un autre résultat important de l'étude est le suivant : un très faible nombre d'événements drainants (de 1 à 6 selon les parcelles) suffit à expliquer 90% des pertes sur une durée de 8 ans. Parmi les systèmes de culture étudiés, le système de culture sans travail du sol est celui qui a engendré les pertes les plus importantes, ce qui pourrait être expliqué par des flux préférentiels du fait d'une bioporosité importante et stable dans le temps. L'étude a également révélé que des systèmes de culture mobilisant une combinaison de pratiques adaptée (réduction des applications herbicides, introduction de cultures intermédiaires, pilotage de

l’irrigation, variété plus précoce) a permis d’obtenir de plus faibles drainages et pertes d’herbicides tout en permettant les objectifs technico-économiques qui leur étaient assignés.

Portée des résultats pour la thèse

Cette étude permet d’éclaircir l’un des enjeux majeurs de la thèse, le lien entre différents systèmes de culture maïsicoles et leur impact sur l’environnement, en prenant pour cas d’étude ici la qualité de l’eau et le mode de transfert par lixiviation qui est majoritaire dans les plaines alluviales irriguées. L’étude montre également que la gestion de l’eau dans les parcelles agricoles doit être à la fois quantitative et qualitative car ces deux aspects sont en lien étroit : le volume drainé est le premier facteur expliquant les pertes en herbicides. La mise en place du système de culture sans travail du sol dans une plaine alluviale où le risque d’érosion est faible à nul interroge en effet puisque ce type de système, en plus de performances économiques moyennes, ne permet pas d’amélioration substantielle de la qualité de l’eau. Ce dernier point permet notamment d’ouvrir la discussion sur la nécessaire territorialisation des systèmes de culture en fonction des enjeux locaux, qui est discuté dans le chapitre V.

Reducing herbicide use and leaching in agronomically performant maize-based cropping systems: an 8-year study

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cite as : Giuliano S, Alletto L, Deswarte C, Perdrieux F, Daydé J, Debaeke P (2021) Reducing herbicide use and leaching in agronomically performant maize-based cropping systems: An 8-year study. Sci of Tot Envi 788, 147695.
https://doi.org/10.1016/j.scitotenv.2021.147695

Abstract

Irrigated maize-based Cropping Systems (CS) are questioned because of the high risk of herbicide transfer to water. An 8-year systemic experiment was conducted to i) compute a multi-performance comparison between a Conventional Maize Monoculture (MM_{Conv}) and four CS that aimed to reduce irrigation and herbicide leaching: MM_{LI}, a low-input MM using cover crop and Integrated Weed Management (IWM) techniques; MM_{Still}, a Strip-tillage MM using cover crop; MM_{CT}, a Conservation Tillage MM with cover crop; Maize-MSW, an IWM Maize rotated with Soybean and Wheat and ii) determine the main drivers and evaluate the influence of CS on herbicide leaching in maize. Drainage water was collected through 1-m depth lysimeter plates and analysed for 6 herbicide molecules and 1 degradation metabolite.
MM_{LI} yielded 10.7 t ha^{-1} close to MM_{Conv} (11.5 t ha^{-1}) despite a lower herbicide use (-57%) and irrigation (-21%). MM_{LI} and Maize-MSW had less drainage events compared to MM_{Conv}. MM_{CT} and MM_{Still} both yielded less (respectively 7.6 t ha^{-1} and 6.2 t ha^{-1}) while their herbicide use increased (both +24%). Mean annual herbicide losses were 0.5±1.0 g ha^{-1} for MM_{LI}, 0.7±1.2 g ha^{-1} for Maize-MSW, 1.3±2.1 g ha^{-1} for MM_{Still}, 2.0±4.8 g ha^{-1} MM_{Conv} and 3.0±9.6 g ha^{-1} for MM_{CT}. Herbicide leaching remained variable but was consistently and mostly influenced by drainage volume. According to the CS, only 1.5 to 6.0 drainage events were responsible for 90% of the herbicide losses. High leaching peaks were identified for mesotrione and glyphosate and may indicate that preferential flows occurred, especially under MM_{CT}. Quantity applied had limited influence on herbicide leaching. To reduce the herbicide leaching risk, CS must concomitantly manage water quality and quantity through a combination of agroecological practices, as in MM_{LI}, a CS able to reach other technical objectives. Present study recommends assessing CS through a diversity of performance indicators.

Keywords: lixiviation, systemic approach, Integrated Weed Management, environmental impact, pesticides

I. Introduction

Widespread production-oriented agriculture is challenged by negative impacts on resource availability, human health and ecosystems, including climate change. To face these critical problems, international and national organizations, farmers and their representatives, researchers, and citizens need to work towards a global agroecological transition through a multifunctional biodiversity-based agriculture at the landscape, farming and cropping system scales (Duru et al., 2015; Huang et al., 2015). In southwestern France, production-oriented agriculture is well represented by maize (*Zea mays* L.) based cropping systems, due to their high profitability, water-use efficiency, high attainable yields (average value of 11.2 t ha^{-1} – Vigneau, 2019) and the lack of profitability of alternative crops.

In southwestern France, conventional maize management consists of (i) two-year rotations or monocultures on 75% of farmland (Renoux, 2016); (ii) a 180 mm ha^{-1} $year^{-1}$ mean irrigation dose applied on average on 80% of the maize acreage (CRAO, 2016); (iii) intensive deep soil tillage, mostly with a mouldboard plough. Moreover, (iv) a high mineral nitrogen fertilization is applied on conventional management (mean value of 184 kg N ha^{-1} - Mas and Dinaucourt, 2019) and results in high CO_2 emissions (Giuliano et al., 2016) and risks of nitrate contamination of rivers and aquifers, especially because of frequent bare soil during fallow periods (Agreste, 2014). Finally, (v) conventional maize management is characterised by a relatively low (2.6) pesticide treatment frequency index (Agreste, 2019) but mainly composed of herbicides causing diffuse pollution in water by leaching or runoff to rivers and aquifers (AEAG, 2018; Steele et al., 2008). In France, most of the detected pesticides in aquifers originate from herbicides applied to maize, such as bentazone, S-metolachlor, deethylatrazine (an atrazine metabolite), with maximum concentrations varying from 25 to 90 µg L^{-1} according to AEAG (2018) and Logan et al. (1994).

Along with runoff, pesticide transport by leaching may impact water quality. When drainage occurs on agricultural soil previously sprayed with pesticides, the drained water is likely to desorb and transport molecules through the soil, the vadose zone and then contaminates aquifers with both parent or degradation products. Four main interacting factors could explain the high herbicide concentration leachates in maize fields: i) climatic conditions, with frequent and intensive spring rain events during the herbicide application period, mostly during the very early maize development stages, ii) physicochemical properties of the molecules, iii) soil properties and iv) cropping practices and particularly tillage, timing and doses of herbicide applications and irrigation management.
Indeed, Alletto et al. (2010) observed from nine studies that annual leaching ranged from 0 to 79.5% of the applied dose across different environments, tillage practices, herbicide applications, and irrigation management. Apart from a study on fluometuron (Essington et al., 1995), the annual amount leached in the experiments studied by Alletto et al. (2010) varied between 0.13% and 3.04% of the applied dose. Tillage influenced some molecules leaching (*e.g.*, higher atrazine leaching under conservation tillage) but was not significant for other molecules (*e.g.*, metolachlor). In a long-term tillage study, Dairon et al. (2017) recorded annual leaching between 0% and 4.4% of the applied dose for various herbicide molecules. A strong

interaction between herbicide application and tillage was observed (*e.g.*, atrazine leaching was reduced under conventional tillage while isoproturon leaching was higher under no-tillage).

In the transition towards a biodiversity-based agriculture (Duru et al., 2015), several options can reduce the use of herbicides and improve quantitative and qualitative water and pesticide management. Soil tillage affects soil variables, mainly structure and porosity, temperature, organic matter content, biological activity, and water dynamics (Tebrugge and During, 1999). In consequence, tillage greatly influences pesticide fate in soil (*e.g.* Licht and Al-Kaisi 2005a; Dam et al. 2005; Alletto et al., 2010). On one hand, soil tillage reduction generally leads to an increase in herbicide use (Colbach and Cordeau, 2018), an accumulation of organic matter in soil surface, a more intense biological activity that may increase pesticide retention and degradation and decrease pesticide transport by runoff and erosion. On the other hand, tillage reduction results in a greater and more stable soil infiltration capacity that may lead to an increase in aquifer contamination risk (Prado et al., 2014). Moreover, little is known on how innovative soil tillage methods such as strip tillage can impact water quality (Alletto et al., 2010; Potter et al., 2015).
Diversified crop rotations reduce the application frequency of the main maize herbicides that transfer into surface water. Particularly in low-input cropping systems, crop rotation including winter crops and/or leguminous species helps to better manage N and P fertilizers (Baffaut et al., 2019) and weed flora (Adeux et al., 2017) on maize in the long term, allowing a consecutive herbicide reduction. A more efficient irrigation management with tensiometers for soil water monitoring, water-saving irrigation equipment and a reduction of water requirements (sowing an earlier-maturing variety) can reduce temporary excess water in the soil and thus, potentially reduce herbicide transfer (Lopez-Pineiro et al., 2017). Cover crops can be a valuable option to reduce drainage water and soil water content at maize sowing, especially when terminated later in the spring (Meyer et al., 2019). Moreover, cover crops can be a powerful tool to manage weeds and mitigate herbicide use (Smith et al., 2020). However, cover crops can necessitate an additional herbicide treatment when chemically terminated. Finally, mechanical, or mixed weeding (combination of banded applications of herbicides and mechanical weeding), can be introduced. Mixed weeding which reduces total herbicide applied from one to two thirds of the original rate is poorly studied but seems promising to reduce the impact of herbicides on water quality (Masters et al., 2013) and to control weed flora (Vasileiadis et al., 2016).

In most of the studies previously cited, only one or two of the above listed options were considered simultaneously. In most of reduced tillage studies, for instance, all other technical operations (*e.g* applied herbicides, irrigation volume, weeding techniques) remained the same between treatments. However, to better fit with the changes observed in soil, sowing density and timing, herbicide applications and irrigation must be adapted to take into account carryover effects (Grassini et al., 2011). Evolution of weed flora composition under reduced tillage should lead to change herbicide molecules used for weeding (Adeux et al., 2017). Moreover, most of the studies remain essentially focused on one environmental issue (*e.g.* herbicide leaching) while other outputs, such as crop productivity, need to be considered and adapted to the regional context. As an example, economic reasons can prevent farmers to substitute monoculture with rotated maize.

The cropping system (CS) approach aims at simultaneously reach objectives on economics, environment, and social wellness. This approach takes advantage of the interactions and carryovers between cropping practices by combining context adapted agroecological practices due to decision rules (*e.g.* the choice of an herbicide molecule and rate according to the weed flora) (Meynard et al., 2003). These levers and rules are included in a more global conceptual framework of Efficiency, Substitution and Redesign (ESR) intended to support transition towards sustainable agriculture (Hill and MacRae 1996). In the case of herbicide water contamination due to conventional maize CS, this framework can help to i) reduce frequency and dose of applied herbicides and ii) limit their transfer to surface water through enhanced retention and degradation processes.

Efficiency aims at reducing external inputs use through their optimisation. Efficiency consists of the usage of the accurate dose with respect to the problem faced (*e.g.*, an herbicide molecule and rate according to the composition and stage of the weed community). For this strategy, Decision Support Tools (*e.g.*, soil humidity probes to manage irrigation) can be useful. Efficiency also includes all the techniques that help to reduce diffuse pollution, such as herbicide spraying in the early morning when air moisture limits herbicide volatilisation (Bedos et al., 2002; Ricci et al., 2011). Substitution aims to replace the use of external inputs with better resource exploitation (*e.g.*, cultivar choice) or by non-chemical inputs such as using mechanical weeding instead of herbicides. Finally, Redesign techniques aim at creating a CS more robust and less susceptible to biotic and abiotic stresses (*i.e.*, resistant and resilient) in order to reduce pesticide use and external inputs. Redesign is more complex to implement because it relies on an appropriate combination of rotation, tillage, cover crop and management (*e.g.* rotation lengthening helps to reduce herbicide use; Liebman et al., 2008).

These Efficiency/Substitution/Redesign techniques (crop rotation, mechanical and mixed weeding, cover crops, reduced tillage) were combined in the present study in four experimental maize-based CS compared with a conventional maize monoculture. These experimental CS were all designed with different strategies to manage weed flora with fewer herbicides in order to protect water quality from herbicide pollution while reaching specific objectives in terms of CS performances (*e.g.* greenhouse gases emissions, gross margin, crop yield). A multicriteria assessment of the CS agronomic performance was used and published by Giuliano et al. (2016). In the present study, the low-input maize-based CS were evaluated on their ability to reduce herbicide leaching over an 8-year period while controlling weed flora and maintaining grain yields.

II. Materials and methods

1. Pedoclimatic context

An 8-year field experiment was carried out at the Domaine de Lamothe — INP PURPAN, Seysses, Garonne Plain, south-western France (43.506N, 1.237E) from 2011 to 2018. The flow chart (Figure IV.1) synthetized the process followed and the data collected in the present study.

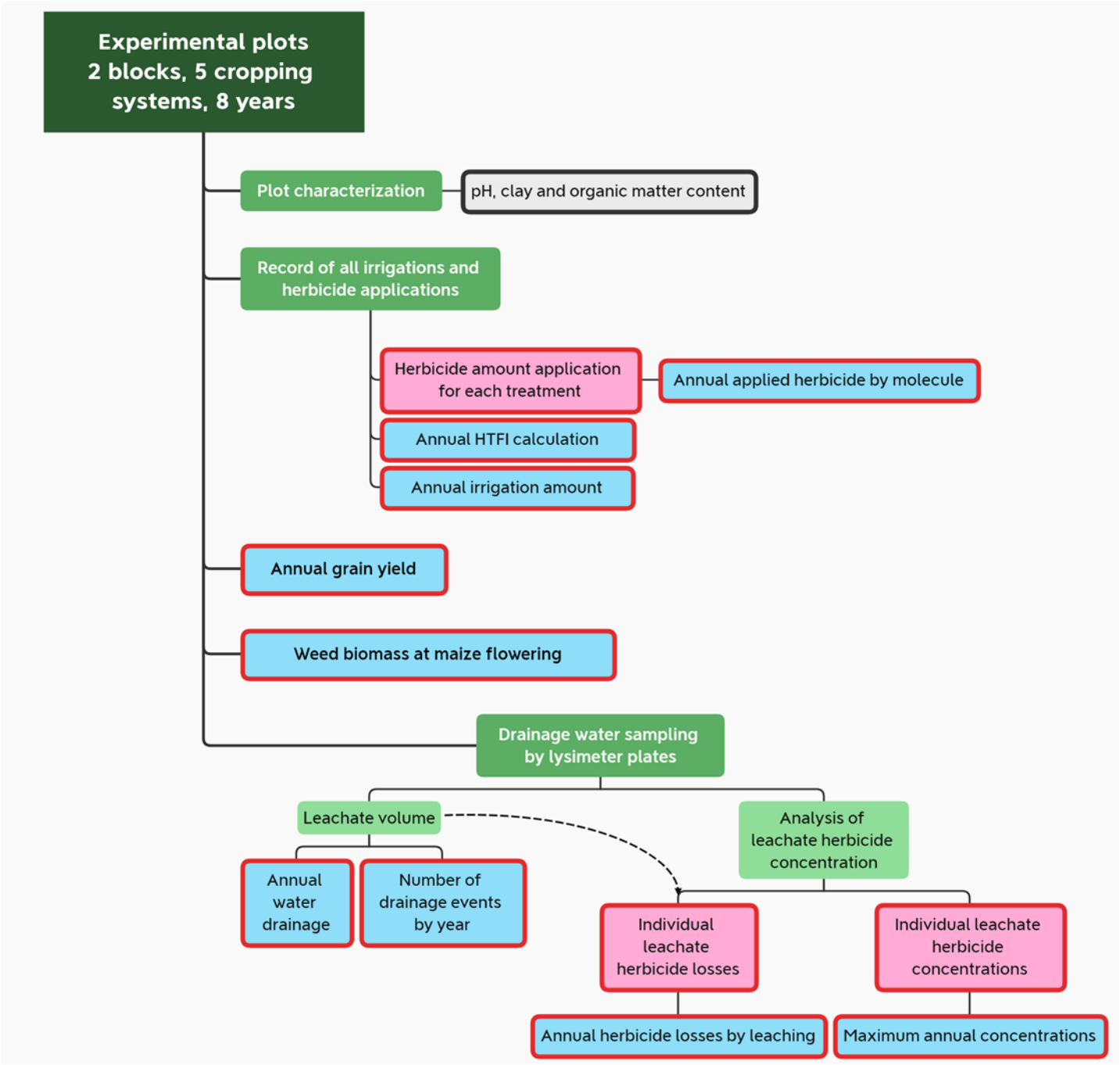


Figure IV.1: Flow-chart of the experiment. The rectangles with red borders are the results presented in the article. Rectangles with light blue background represent data from the annual dataset. Rectangles with light pink background represent data data from the individual dataset.

The soil was identified as a stagnic Luvisol according to the World Reference Base for Soil Resources (FAO, 2006) with some disparities between blocks and unit plots, ranging from 22.5% to 49.5% of clay and an average of 18.8 g kg^{-1} of organic matter (supplementary material n°1). The climate of the experimental zone is mainly Atlantic with Mediterranean and continental influences with a frequent water deficit between June and September (Figure IV.2). During the study, the month with the highest mean rainfall was May with 84 mm and the driest was September with 29 mm. During the maize cropping season noticeable wet springs occurred in 2013, 2017 and 2018 while 2011 and 2015 were characterized by severe dry springs. Monthly average temperatures ranged between 6.0°C (February) and 22.1°C (August). Until 2010, the experimental site was conducted homogeneously with a sunflower-soft wheat rotation. S-metolachlor, both used on the experiment and on sunflower (last time in 2009), was systematically analysed on the first years of the experimentation.

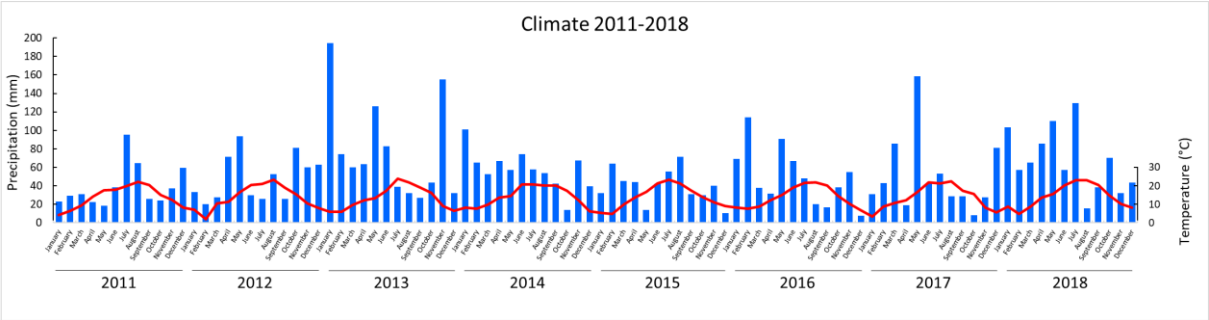


Figure IV.2: Ombrothermic diagram during the experiment (2011-2018). Data from Domaine de Lamothe automatic weather station. During the maize cropping season (approximately April-October) important plots flooding occurred in May 2013 (especially on Maize-MSW and on MM_{LI} that could not be ploughed that year), in May 2017 and in spring 2018 while severe dry springs occurred in 2011 and 2015.

2. Cropping systems description and comparison

Four alternative CS were compared to a conventional Maize Monoculture (MM_{Conv}) (Figure IV.3 and supplementary material n°2 for the annual applications of monitored herbicides).

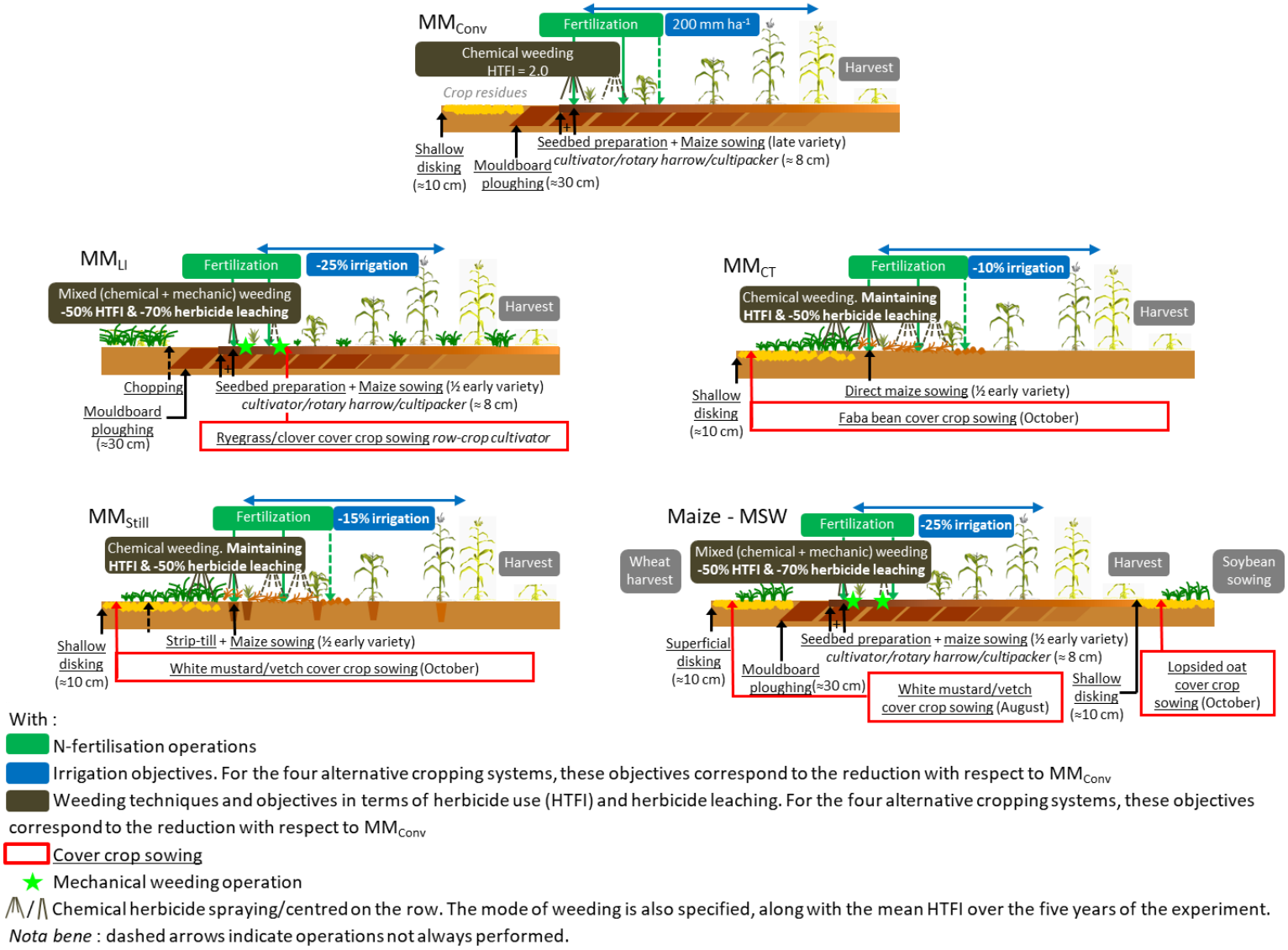


Figure IV.3: Schematic describing the five cropping systems tested in the experiment. MM_{Conv} is the conventional Maize Monoculture (MM), MM_{LI} is the low-input MM, MM_{CT} is the conservation tillage MM, MM_{Still} is the strip-till MM and Maize-MSW is the Maize rotated with soybean and wheat. HTFI is the Herbicide Treatment Frequency Index.

MM_{Conv} was designed to replicate the high input practices used in southwestern France to maximize yield and gross margin. Irrigation was managed to cover 100% of the maximum evapotranspiration (ET), in accordance with the local recommendations (Maruejouls and Routelous, 2020) and excesses were avoided through the monitoring of soil water reserve with tensiometers. A spring mouldboard ploughing followed by a rotary harrowing was performed after a bare soil during fallow period (residue burial). After sowing, an herbicide mix of S-metolachlor and mesotrione was applied in broadcast application, usually before emergence. When weed pressure was high (5 years out of 8), a curative herbicide application at the 8-leaves stage composed of varied mixtures of mesotrione, nicosulfuron and dicamba was done. For each CS, annual herbicide doses applied are specified in supplementary material.

MM_{LI}, a Low-Input Maize Monoculture aimed to reduce pesticide application and water pollution from herbicide leaching by 70% without reducing economic margin with respect to MM_{Conv}. Compared with MM_{Conv}, HTFI (Herbicide Treatment Frequency Index) (eq. 1) was aimed at being halved.

$$\text{HTFI} = \sum_i \frac{(Applied\ dose)_i \times (Treated\ surface\ area)_i}{(Reference\ dose)_i \times Plot\ area} \quad [1]$$

To maintain a similar weed pressure to MM_{Conv}, banded applications of herbicides on the seed row at sowing followed by mechanical weeding (rotary hoe and row crop cultivator) were performed. The same curative herbicides molecules as MM_{Conv} were broadcasted (1 year out of 8, when perennial weeds were present) or banded applied at row crop cultivator timing (3 years out of the 8, when weed pressure on the row was high). Irrigation water was aimed to be reduced by 25% with respect to MM_{Conv}: an earlier-maturing variety was sown, and only 90% of the maximum ET was covered. To improve soil and water protection, a winter cover crop (*Lolium hybridum* + *Trifolium* spp.) was grown during the fallow period. Mouldboard ploughing was performed in spring, both to bury the cover crop without herbicide and to ensure good maize development. In 2013, a flood over the two MM_{LI} experimental plots prevented ploughing: reduced tillage was used and the cover crop was suppressed by glyphosate.

MM_{CT}, a Conservation Tillage Maize Monoculture aimed to reduce pesticide leaching by 50% compared to MM_{Conv} due to the introduction of a winter cover crop (*Faba bean* L.), a drastic reduction in tillage and a reduction of 10% of irrigation water compared to MM_{Conv}. Maize was sown after strip tillage in 2011 and 2012, and since 2013, directly without tillage. Techniques and decision rules for irrigation were similar to MM_{LI}. To maintain acceptable weed management, weeds were controlled exclusively with chemicals with the objective to level MM_{Conv} HTFI. However, a slightly different herbicide combination was applied since 2013, where the use of S-metolachlor as a pre-emergence herbicide was substituted with a post-emergence application of mesotrione, nicosulfuron, dicamba and/or S-metolachlor.

MM_{Still}, a Strip Tillage Maize Monoculture aimed to reduce pesticide leaching by 50% compared to MM_{Conv}. Cover crops were introduced: perennial white clover (*Trifolium repens* L.) from 2011 to 2013, and then a winter mixture of white mustard (*Sinapis alba* L.) and common vetch (*Vicia sativa* L.). Seedbed preparation was achieved in spring with a strip-tillage, sometimes preceded by autumn strip-tillage to improve soil structure. MM_{Still} had also the objective to maintain the same level of irrigation than MM_{Conv} water until 2013 then to reduce it by 25% in 2014, using the same techniques as in MM_{LI} and MM_{CT}. With respect to MM_{Conv}, MM_{Still} aimed at stabilizing herbicide use. Cover crops were suppressed with glyphosate and

2,4-D applications. For 2011-2013, crop weed management relied essentially on bentazone, as this molecule was authorized both for use in clover and maize. Since 2014, weeding combined a localized application of mesotrione and S-metolachlor on the row crop at sowing followed by a systematic post-emergence broadcast application of mesotrione, nicosulfuron and dicamba. In 2013 and 2018, strong competition with clover and weeds stopped maize development and the crop was not harvested.
Maize-MSW, a Maize rotated with Soybean and soft Wheat in a CS designed to reduce HTFI and irrigation water at the rotation level by 50% compared to MM_{Conv}. A *Sinapis alba* L. + *Vicia sativa* L. cover crop was present before maize. At the maize crop level, Maize-MSW had the same input reduction objectives and management strategy as MM_{LI}, reducing HTFI by 50% and irrigation water by 25% to reduce pesticide leaching by 70%. Before maize sowing, the cover crop was buried by an autumn mouldboard ploughing but in 2016, glyphosate was applied before maize sowing since *Lolium* sp. was too developed for mechanical destruction. Only results from the maize sequence of the rotation are presented here because too few leachates were analysed in soybean and wheat.

3. Experimental design

Each CS and each crop of Maize-MSW was carried out every year on two 720 m² plots, arranged as two complete randomized blocks. The best compromise between the conditions of the two plots was done to carry out the same operations on the same day for both plots of a given CS.

4. Cropping system agronomic performances

CS performances were assessed using grain yield and weed biomass at maize flowering. Grain yield was measured by hand harvesting two uniform and representative 10 m² zones per plot in 2011-2013, and then by hand harvesting four 10 m² zones per plot in 2014-2018 to better take into account plot heterogeneity. Samples were then oven-dried for 48h at 80°C and weighed. Yields are presented in t ha^{-1} at the 15% moisture commercial standard. Weed biomass at maize flowering was sampled within two 1 m² fixed quadrats (2011 to 2013) then within four 0.5 m² (2014 to 2018) fixed quadrats per plot to better take into account plot heterogeneity. Species were then identified and separated, oven-dried for 48h at 80°C and weighed.

5. Leachate collection and pesticide analysis

Because field slope was less than 1 %, water runoff was negligible. Drainage water and pesticide leaching were monitored on each plot through 0.075 m² tension plate lysimeters (SIC300, UMS GmbH, München, Germany) installed at a 1.0 m-depth. A −100 cm tension was fixed in the plate lysimeter throughout maize cropping.
The water table level was monitored, and leachate sampling was decided to be stopped when water table was close to the lysimeter plate. Every year, drainage monitoring lasted on the same

period on all plots with a duration depending on the water table depth. Drainage monitoring usually started before the first maize herbicide application, except in 2013 because of a post—sowing flooding, and usually stopped in December. During this period, water accumulated by the plate lysimeter was collected with a vacuum pump approximately every two weeks or as needed by the drainage volume. In Maize-MSW, monitoring only occurred where maize was cropped, thus each plot of the rotation MSW was monitored only one year out of three.

The leachate samples obtained were then kept at 4°C until analysis. Leachates with a volume above 100 mL (equivalent of a 1.3 mm ha^{-1} drainage) collected on plots where at least one herbicide was applied earlier in the season were subject to be analysed for all the molecules applied. For technical (volume of the leachate) and economical (cost of the analysis) reasons, all samples and all molecules were not analysed. Samples and molecules were prioritized according to the importance of the molecules in the CS, volume and timing of the leachate. When successive close drainage events were recorded in a plot, the samples were bulked and analysed, according to the original proportion of each leachate collected.

Six molecules and one main degradation metabolite of glyphosate (AMPA, aminomethyl phosphonic acid) were monitored during the experiment. The samples were analysed at the Laboratoire Départemental d'Analyses de la Drôme (Valence, France), accredited by COFRAC (COmité FRançais d'ACcréditation). A specific analysis is provided in the results for the two main S-metolachlor metabolites, metolachlor-ethane sulfonic acid (ESA) and oxalic acid (OXA), that started to be quantified only from 2016, when they were about to be considered as pertinent by the regulation (ANSES, 2019). The quantification limit (QL) of each herbicide is mentioned in Table IV.1 along with their physicochemical properties. When a molecule was not detected (detection limit was QL/3), it was considered to have a null concentration. If it was detected but not quantified, the concentration retained was the detection limit.

Molecule	QL (µg L^{-1})	Koc (L kg^{-1})	Field DT50 (days)	Solubility in water at 20°C (mg L^{-1})	log Kow	Vapor pressure at 20°C	GUS	Indication on leachability
glyphosate	0.03 to 0.05	1424 (884-50660)	23.8 (5.7-40.9)	10500	-3.2	0.0131	-0.25	low leachability
AMPA	0.03 to 0.05	2002	419 (283.6-633.1)	1466561	-1.63	-	0.03	low leachability
S-metolachlor	0.02	226 (110-369)	21 (11-31)	480	3.05	3.7	1.9	transition state
bentazone	0.02	55.3 (13-176)	7.5 (3.0-31.3)	7112	-0.46	0.17	2.89	high leachability
mesotrione	0.01	122 (15-390)	5 (3-10)	1500	0.11	0.0057	2.69	low leachability
nicosulfuron	0.01 to 0.02	30	19.3 (8.9-63.3)	7500	0.61	$8x10^{-7}$	3.24	high leachability
dicamba	0.04	5.1	3.9 (3.2-4.9)	250000	-1.88	1.67	1.75	low leachability

Table IV.1: Physicochemical properties of the molecules monitored during the study. All data from PPDB (2020) except Koc for S-metolachlor (EU COMMISSION, 2004) and dicamba (EFSA, 2011)

6. Characterisation of water dynamics

CS were compared for their impacts on water dynamics through four indicators. Firstly, cumulative drainage water per cropping season (in mm) was calculated as:

$$Drainage\ water = \frac{\sum_{i=1}^{k} Volume\ measured_i}{S} \quad [2]$$

Volume measured is the volume of the leachate in mL and S is the surface of the lysimeter plate (in m^2).

Secondly, the herbicide losses by leaching (in g ha^{-1}) were quantified for each plot and calculated as:

$$Herbicide\ losses = \frac{\sum_{i=1}^{k} Concentration_i\ x\ Water\ drainage_i}{100} \quad [3]$$

i is a a given sample and *k* the number of samples per plot. *Concentration* is the herbicide concentration in µg L^{-1}.

Finally, the herbicide losses registered annually for each molecule on each cropping system were divided by the annual applied dose of the molecule to estimate the percentage of losses by leaching. To calculate this ratio, it was considered that molecules applied the year before were absent in the soil profile the next season as suggested by Marín-Benito et al., (2014).

7. Data analysis

Plot was the statistical unit in the experiment except for HTFI and irrigation since the same management was applied each year on both plots of a CS. Two datasets were analysed:

i. the *individual dataset* recorded the herbicide concentrations and losses measured on each sample for each molecule and for the total concentration of the seven molecules monitored.
ii. the *annual dataset* recorded the annual sum of herbicide losses by leaching, the annual maximum of concentration and the frequency of detection for each molecule and for the total concentration of the seven molecules monitored. The annual dataset excluded bentazone since this molecule was only searched in 2012.

Environment and CS influences on herbicide concentrations and losses were evaluated on both datasets. First, herbicide concentrations and losses were transformed with log(x+0.01) to include null concentrations while improving normality and homogeneity of the residuals. The following linear regression was selected as the starting equation for the model selection:

$$Y_{ij} = cropping\ system_i + clay + organic\ matter + pH + drained\ volume + DALT + dose\ applied + \varepsilon_{ij} \quad [4]$$

This equation took into account *cropping system*, soil characteristics of each plot (*clay* and *organic matter* contents, *pH*) and characteristics of the sample (*drained volume*; *DALT*, the number of Days After the Last Treatment with the given molecule; and *dose applied*, the amount of molecule applied on the plot previously during the cropping season). Once this regression was performed for each molecule, the normal distribution of the residuals with respect to the fitted values was verified with a Shapiro-Wilk test with α=0.05. The few residuals without normal distribution are indicated in italics in the tables. The same linear regression as [4] was performed on the annual dataset for the model selection but, in that case, *dose applied* was the total annual applied amount of the given molecule and *DALT* was not retained since it was not relevant for annual data.

Both for individual and annual data, the model quality was evaluated with the adjusted R^2 and was selected with the lowest Akaike Information Criterion (AIC) that contained only the relevant variables. For that, a stepwise selection was made, using the function *step()* of the package *MASS* from statistical software R (R Core Team, 2018). Finally, the relative importance of each variable retained in the best model according to the AIC procedure was calculated with the function calc.relimp() of the package *relaimpo* from R.

To compare CS, since data did not assume a normal distribution, a non-parametric Kruskal-Wallis test followed by a Steel-Dwass-Critchlow-Fligner multiple comparisons procedure were performed on the annual dataset. CS and year were the two factors studied and were tested without interactions. This model was also used for agro-environmental data. For grain yield and irrigation, after verification that their residuals passed the Shapiro-Wilk test, an ANOVA followed by a *post-hoc* Fisher-LSD mean comparison was computed. For weed biomass at maize flowering, HTFI and total annual herbicide losses, comparisons between cropping systems and between years were performed with a Kruskal-Wallis test followed by a Steel-Dwass-Critchlow-Fligner multiple comparisons procedure with α=0.05.

8. Multicriteria assessment

The reach of the objective initially fixed for the four alternative CS was finally calculated for each performance but grain yield as a relative gap calculated as:

$$relative\ gap = 1 - \left(\frac{\text{mean in alternative CS on } 2011-2018}{\text{mean in } MM_{Conv}}\right)/\%\ of\ the\ initial\ objective\ fixed \quad [5]$$

For grain yield, the reach of all the criteria but grain yield for which it was:

$$relative\ gap = -1 + \left(\frac{\text{mean in alternative CS on } 2011-2018}{\text{mean in } MM_{Conv}}\right)/\%\ of\ the\ initial\ objective\ fixed \quad [6]$$

III. Results

1. Agro-environmental evaluation

a) Grain yields (Figure IV.4.a)

Yield varied significantly from 5.5 ± 3.3 t ha^{-1} in 2013 to 11.8 ± 3.2 t ha^{-1} in 2017. Years that had the lowest yields for all CS but MM_{Conv} were 2013 and 2018. 2013 and 2018 were especially detrimental for MM_{Still} that could not be harvested in those years. MM_{Conv} (11.5 ± 2.3 t ha^{-1}) and MM_{LI} (10.7 ± 2.9 t ha^{-1}) gave the best yields (Figure 4.a). MM_{Conv} yielded significant more than Maize-MSW (9.6 ± 2.1 t ha^{-1}). MM_{Conv}, MM_{LI} and Maize-MSW, all three based on annual ploughing, yielded significantly more than the two reduced tillage CS: MM_{CT} (7.6 ± 3.3 t ha^{-1}) and MM_{Still} (6.2 ± 4.0 t ha^{-1}).

b) Weed biomass

Weed biomass was highly variable across years, ranging from 6 ± 6 g m^{-2} in 2015 and 7 ± 7 g m^{-2} in 2016 to 257 ± 294 g m^{-2} in 2018. MM_{CT} had the highest weed biomass at flowering (142 ± 217 g m^{-2}) while the other MM with reduced tillage, MM_{Still}, was the second weediest CS (80 ± 125 g m^{-2}) (Figure IV.4.b). However, MM_{Still} weed biomass was not monitored in 2013 and 2018 because high weed biomass led to crop failure. Maize-MSW had a 40 ± 61 g m^{-2} weed biomass at flowering and grouped together with MM_{CT} and MM_{Still}. Finally, MM_{LI} and MM_{Conv} had the lowest weed biomass with 32 ± 51 g m^{-2} and 23 ± 31 g m^{-2}, respectively (Kruskal-Wallis, $p<0.05$). The higher weed biomass on the two reduced tillage CS (MM_{Still} and MM_{CT}) was associated with higher *Echinochloa crus-galli* and *Convolvulus arvensis* biomass than the other CS (see Adeux et al. (2017) for more details on weed flora dynamics).

Interaction between CS and years was also present. For example, 2012 showed low weed biomass for the three CS that included ploughing (21 ± 17 g m^{-2} for MM_{Conv}, 7 ± 7 g m^{-2} for MM_{LI} and 32 ± 7 g m^{-2} for Maize-MSW) while weed biomass was 64 ± 26 g m^{-2} and 131 ± 64 g m^{-2} in MM_{CT} and MM_{Still}, respectively.

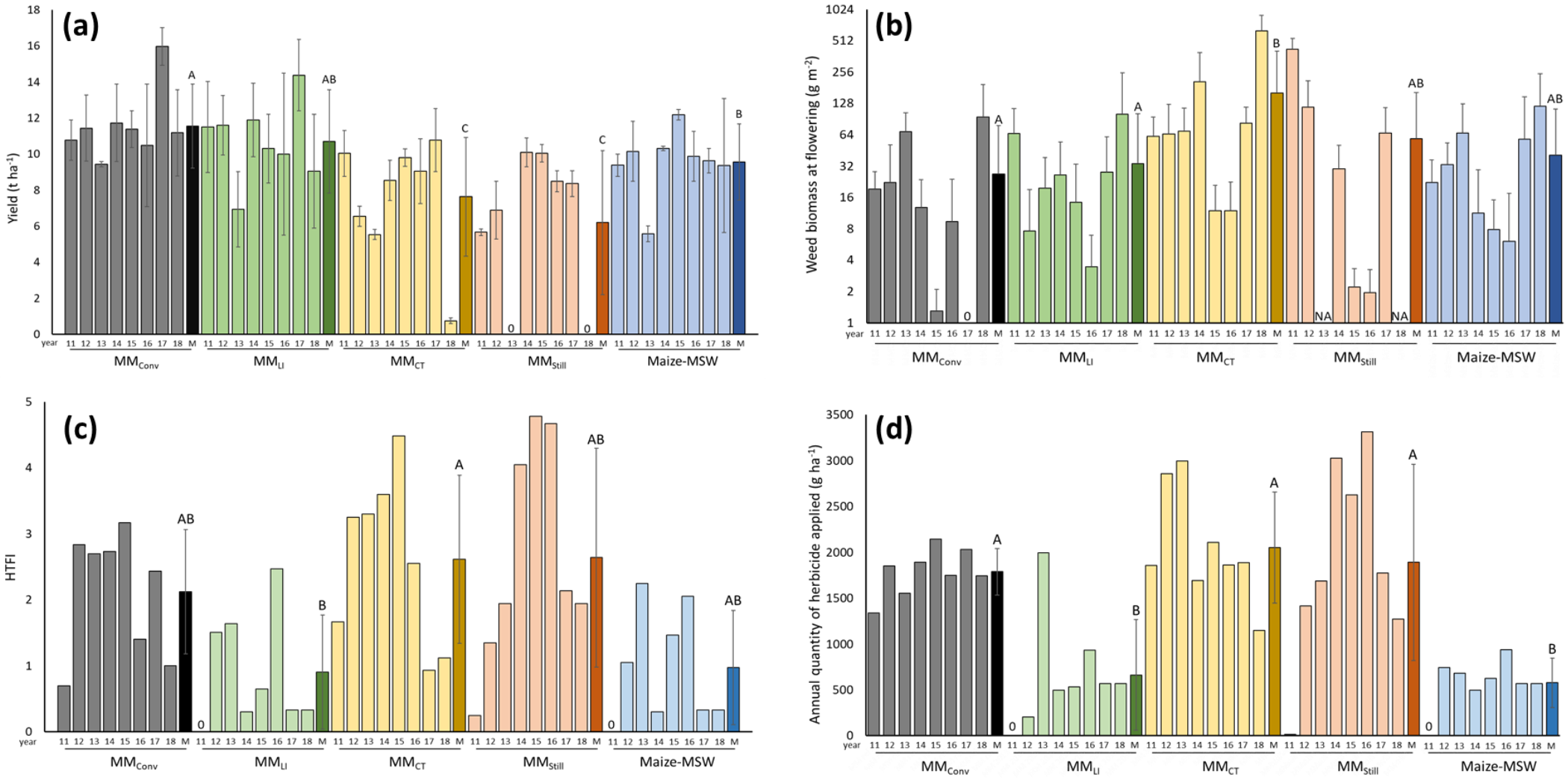


Figure IV.4: Technical performance of the CS in 2011-2018. a: Mean grain yields at 15% grain moisture (t ha-1). b: Log+1 of weed biomass measured at maize flowering. c: Herbicide Treatment Frequency Index. d: Mean annual herbicide amounts applied (g ha-1). Error bars indicate the standard deviation. Letters on the mean value of a CS indicate groups according to a post-hoc Fisher-LSD test with α=0.05. For each CS, the light bars indicate the annual yields from 2011 to 2018 and the dark bar indicates the mean value on 2011-2018 period.

c) Herbicide use: quantity of herbicides applied and HTFI

HTFI varied from 0.5 ± 0.7 in 2011 to 2.7 ± 1.2 in 2016. The two alternative CS with ploughing, MM_{LI} (0.9 ± 0.9) and Maize-MSW (1.0 ± 0.9), both exceeded their objective to halve HTFI with respect to MM_{Conv} (2.1 ± 0.9) (Figure IV.4.c). On the other hand, HTFI in MM_{Still} and MM_{CT} increased by 24% with respect to MM_{Conv} (respectively 2.6 ± 1.7 and 2.6 ± 1.3), even if not statistically significant (p=0.25). Interaction between year and CS was also very important, particularly because weed flora changed and led to weeding techniques changes across years and CS.

The annual variation in amount of applied herbicide followed the same pattern as HTFI and ranged between 642 ± 840 g ha^{-1} in 2011 and 1761 ± 917 g ha^{-1} in 2016. Herbicide amount applied in MM_{LI} and Maize-MSW were 662 ± 604 g ha^{-1} and 578 ± 270 g ha^{-1}, respectively. This amount was reduced by 63% and 68% compared with MM_{Conv} (1788 ± 256 g ha^{-1}) (Figure IV.4.d). Amount applied in MM_{CT} (2052 ± 607 g ha^{-1}) and MM_{Still} (1891 ± 1072 g ha^{-1}) was slightly higher than MM_{Conv} but not statistically different. The six herbicides monitored in the experiment accounted for 100% of the molecules applied to MM_{Conv}, MM_{LI} and Maize-MSW, 92% of those applied to MM_{CT} and 86% of those applied to MM_{Still}. Herbicides applied but not monitored were 2,4-D, tembotrione, isoxadifen-ethyl, quizalofop-p-ethyl, all in MM_{CT} and MM_{Still}.

d) Irrigation

Important annual irrigation was highly variable across years and ranged from 122 mm in 2014 to 266 mm in 2012, according to the summer precipitations (Figure 2). Irrigated water supply in MM_{Conv} was 229 ± 52 mm on average, significantly (Fisher-LSD test, $p<0.05$) higher than MM_{CT} (196 ± 47 mm), MM_{LI} (181 ± 38 mm) and Maize-MSW (186 ± 36 mm). MM_{LI} and Maize-MSW irrigation was reduced by 21% and 18% respectively, a bit less than the objective fixed in the study (25% of reduction) while MM_{CT} reached the study objective to reduce irrigation by 10%. MM_{Still} (214 ± 51 mm) also reduced irrigation water use with respect to MM_{Conv} but to a lesser extent.

e) Drainage

Across all CS and years, 1288 drainage checks were performed and 562 leachates were collected. Mean annual drainage water at 1-m depth occurred for 3.6 events/year (e/y) in average and represented a volume of 63 mm. 2011 and 2015 experienced significantly (Kruskal-Wallis test, $p<0.05$) less drainage (18 and 31 mm, respectively) than the other years. Conversely, in 2014, a year characterised by intensive rain events in May and June (Figure IV.2) and low irrigation, resulted in significantly (Kruskal-Wallis test, $p<0.05$) higher drainage than all other years (96 mm in average, up to 131 mm ha^{-1} in MM_{Still}) despite a number of drainage events close to the average (3.3 e/y).

MM_{Still} (70.8 ± 49.0 mm) and MM_{Conv} (62.8 ± 36.6 mm) had the highest average amounts of drained water (Table 2) but there were not statistical differences between cropping systems on that variable. MM_{Conv} (4.7 ± 2.2 e/y) and MM_{Still} (4.1 ± 2.0 e/y) had significantly more annual drainage events than MM_{LI} (2.6 ± 1.6 e/y) and Maize-MSW (3.1 ± 2.1 e/y) (Kruskal-Wallis test, $p<0.1$, Table IV.2). MM_{CT} was intermediate with 3.6 ± 2.1 e/y.

Cropping system	Average volume (mm)	Annual number of drainage events
MM_{Conv}	62.8 ± 36.6 a	4.7 ± 2.2 a
MM_{LI}	50.3 ± 29.5 a	2.6 ± 1.6 c
MM_{CT}	52.3 ± 38.1 a	3.6 ± 2.1 abc
MM_{Still}	70.8 ± 49.0 a	4.1 ± 2.0 ab
Maize-MSW	47.9 ± 41.5 a	3.1 ± 2.1 bc

Table IV.2: Average number of water drainage events and mean annual water drainage recorded per CS from 2011 to 2018. Mean ± standard deviation, CS that do not share a common lower-case letter within a column are significantly different (Kruskal-Wallis test) at $P \leq 0.1$

f) Herbicide detections in drainage water

In all, 219 leachates fulfilled the conditions for analysis. Among them, 130 were effectively analysed as discussed before: 39 came from MM_{Conv}, 30 from MM_{CT}, 28 from MM_{Still}, 17 from MM_{LI} and 16 from Maize-MSW. Four molecules (bentazone, mesotrione, nicosulfuron and S-metolachlor) were detected in 78% to 83% of the samples and associated with high maximum concentrations and higher frequencies at concentrations above 1µg L^{-1} and 10 µg L^{-1} (Table IV.3). These four molecules had a relatively low Koc but mesotrione was the only one characterized by a 'low leachability' (Table IV.1). On the other hand, glyphosate, AMPA and dicamba, all considered as low leachable molecules, were detected in less than 50% of the samples and almost never detected above 1µg L^{-1}.

	glyphosate	AMPA	S-metolachlor	mesotrione	nicosulfuron	dicamba	bentazone
number of analysis	41	36	74	112	78	29	6
detection frequency	39%	47%	89%	82%	78%	31%	83%
frequency [C]>1µg L^{-1}	5%	0%	36%	20%	18%	3%	67%
frequency [C]>10µg L^{-1}	0%	0%	0%	3%	1%	3%	17%
max. [C] (µg L^{-1})	1.31	0.91	9.17	28.96	12.8	10.39	11.5

Table IV.3: Characteristics of the molecules recorded in the 130 leachates analysed on the five CS. [C] = concentration

2. Main factors influencing herbicide concentration in drainage water (Table IV.4)

On individual dataset, adjusted R^2 to explain each herbicide molecule concentration ranged from 0.17 (mesotrione) to 0.52 (dicamba) if bentazone (*n*=6) was excluded. The adjusted R^2 for the total herbicide concentration was 0.13. On annual data, across all CS and years, mean annual maximum concentration was 3.30 ± 7.26 µg L^{-1}. The linear models' quality ranged from 0.20 to 0.73 adjusted R^2 (data not shown) for annual maximum concentration.

Molecule	n	adjusted R^2	drainage volume	% clay	% organic carbon	pH	applied quantity	days after last application	cropping system
total	130	0.13 ***	81% ↗ *		19% ↗ 0.11			Not tested	
glyphosate + AMPA	41	0.34 **	35% ↗ *			14% ↘ °			51% MM_{Still} : ↗ ° MM_{CT} : ↗ ° Maize - MSW : ↗ **
S-metolachlor	74	0.27 ***	20% ↗ *	11% ↗ *		5% ↘ °	2% ↘ 0.14	48% ↘ ***	13% MM_{Still} : ↘ ° MM_{CT} : ↗ 0.14
mesotrione	112	0.17 ***	38% ↗ **					62% ↘ ***	
nicosulfuron	78	0.30 ***	50% ↗ ***		30% ↗ **			20% ↘ *	
dicamba	*29*	*0.52* ***		*25%* ↘ *	*13%* ↗ *	*23%* ↗ **			*39%* *MM_{CT} :* ↘ ** *MM_{Still} :* ↘ **
bentazone	6	0.99 ***	14% ↘ *					86% ↘ ***	Not tested

Table IV.4: Linear regressions models computed to explain the leachate herbicide concentrations observed in the 130 samples studied (individual dataset). *n* indicates the number of leachates measured. The variables retained in the model have a white background. ↗ and ↘ indicate the meaning of the correlation. The p-values for the significance of a variable used in the model are presented as: *** <0.001, ** <0.01, *<0.05, °<0.1 and the significance level of the variables retained in the model with p-values>0.1 are indicated. For each molecule, the relative importance of the variable retained in each model is indicated with the percentage. Molecules in italics are the ones from which the residuals do not follow a normal distribution.

a) Effect of drainage volume

On the individual dataset, total herbicide leachate concentrations of glyphosate+AMPA, S-metolachlor, nicosulfuron, mesotrione increased with leachate volume, with a relative importance above 20%. For nicosulfuron and total herbicide, drainage volume was the most significant variable of the regression accounting with 50% and 81% relative importance, respectively.

These observations are consistent with the annual dataset: drainage volume was positively correlated with the annual maximum concentration for all molecules except dicamba. Drainage volume was the main factor explaining the maximum concentration recorded each year on each plot for mesotrione (78% relative importance for a 0.40 adjusted R^2), S-metolachlor (51% relative importance for a 0.20 adjusted R^2) and the total herbicide concentrations (98% for a 0.49 adjusted R^2). Finally, drainage volume was also an important variable for nicosulfuron (43% for a 0.36 adjusted R^2) and glyphosate+AMPA (27% for a 0.38 adjusted R^2).

b) Effect of soil variables

On the individual dataset, soil variables to explain herbicide concentrations had a relative importance that varied from 5 to 30% of the total adjusted R^2. Clay, Soil Organic Carbon (SOC) and pH influenced the concentrations measured for glyphosate+AMPA, S-metolachlor, nicosulfuron, dicamba and total active ingredients. Clay, SOC and pH influence was not consistent across molecules: *e.g.*, clay content had a positive influence on S-metolachlor concentration but a negative influence on dicamba concentration, probably because of the differences in their physical properties. Nicosulfuron leachate concentration tended to increase with the SOC content with a 30% relative importance. Dicamba leachate concentrations decreased with higher clay content (relative importance of 25%) while a more basic pH increased the dicamba concentrations (relative importance of 23%).

At the annual scale, pH, SOC and clay content had little influence on the maximum concentrations recorded, with a relative importance between 2 to 12%. In contrast to drainage volume, variables involved to explain the variation of each molecule were not consistent between datasets: *e.g.* a more basic pH reduced AMPA+glyphosate individual concentrations but increased annual maximum AMPA+glyphosate concentrations.

c) Influence of application: quantity and days after last treatment

On the individual dataset, the applied quantity only correlated with S-metolachlor with a 2% relative importance and this relationship was, surprisingly, negative. This counterintuitive result needs to be considered carefully for individual data since, after a given application, several leachates can have null or low concentrations if the molecule has not reached the 1 m depth lysimeter plate.

Moreover, the two main S-metolachlor metabolites, metolachlor-ethane sulfonic acid (ESA) and oxalic acid (OXA) were monitored in the experiment only from 2016 to 2018. Sixteen leaching samples were analysed for ESA and OXA: 5 from MM_{Conv}, 5 from MM_{LI} and 3 from Maize-MSW. While S-metolachlor mean concentrations on these samples were 1.91 µg L^{-1} in MM_{Conv}, 1.20 µg L^{-1} in MM_{LI} and 5.37 µg L^{-1} in Maize-MSW, mean ESA+OXA concentrations were, respectively, 20.47, 21.84 and 12.32 µg L^{-1}. In those years, application doses of S-metolachlor varied from 450 g ha^{-1} for MM_{LI} and Maize-MSW to 1500 g ha^{-1} for MM_{Conv}.

The annual quantity applied was a more significant and consistent variable to explain annual maximum concentrations. Annual quantity increase was significantly linked with bentazone (93% of a 0.73 R^2), dicamba (80% of a 0.20 R^2), glyphosate+AMPA (61% of a 0.38 R^2), S-metolachlor (49% of a 0.21 R^2) and mesotrione (18% of a 0.40 R^2) maximum annual concentrations.

On individual data, Days After the Last Treatment (DALT) increase induced a reduction of leachate concentrations for S-metolachlor, mesotrione, nicosulfuron and bentazone. For bentazone, mesotrione and S-metolachlor concentrations, DALT was the most explaining variable and accounted for 86%, 62% and 48% of the total variability explained by the model, respectively.

d) Effect of cropping system

Within the individual dataset, CS had a significant effect on glyphosate+AMPA (adjusted R^2 of the model was 0.34), dicamba (adjusted R^2=0.52) and S-metolachlor (adjusted R^2=0.27) leaching concentrations with relative importances of 51%, 39% and 13%, respectively. CS was the most influential parameter for glyphosate+AMPA and dicamba. The Glyphosate+AMPA concentration model was higher for MM_{CT} and MM_{Still}, both CS using glyphosate frequently, and for Maize-MSW that had a single sample analysed with a 1.22 µg L^{-1} concentration in the only year this molecule was applied. Conservation tillage CS (MM_{Still} and MM_{CT}) showed proportionally lower dicamba concentrations. For S-metolachlor, MM_{CT} had proportionally higher S-metolachlor leaching concentrations, and MM_{Still} had significantly reduced S-metolachlor concentrations.

In the annual dataset, annual maximum nicosulfuron concentrations were mostly explained by CS (57% relative importance of the 0.36 R^2 relationship). MM_{Conv} and MM_{Still} induced higher nicosulfuron maximum concentrations compared with the other CS. Indeed, MM_{Still} (1.00 ± 1.76 µg L^{-1}) and MM_{Conv} (0.48 ± 1.24 µg L^{-1}) had significative (Kruskal-Wallis test at $p<0.1$) higher mean annual maximum nicosulfuron concentrations than MM_{LI} (0.11 ± 0.31 µg L^{-1}) and Maize-MSW (0.00 ± 0.00 µg L^{-1}).

3. Drivers of herbicide losses by leaching

Linear regression models on individual herbicide losses varied from 0.25 to 0.57 adjusted R^2 (bentazone excluded) and were highly influenced by drainage volume. Indeed, drainage volume was the main driver of herbicide losses for all molecules with a relative importance from 55% to 100%. At the annual scale, the adjusted R^2 for the herbicide losses ranged from 0.09 to 0.62 (Table IV.5). With 50% to 98% of the total adjusted R^2, drainage volume was also the main driver for all molecules except dicamba. The relationship between estimated total herbicide annual loss and drainage volume was particularly relevant with a relative importance of 98% of the 0.62 adjusted R^2 (Figure IV.5).

Molecule	adjusted R^2	Model p-value	post-application drainage volume			Applied herbicide quantity		
total	0.62	***	98%	↗	***			
glyphosate + AMPA	*0.39*	***	*50%*	↗	***	*43%*	↗	***
S-metolachlor	*0.23*	***	*67%*	↗	***	*33%*	↗	***
mesotrione	0.48	**	*89%*	↗	***			
nicosulfuron	*0.41*	***	*63%*	↗	***	*9%*	↗	*0.170*
dicamba	*0.09*	*				*74%*	↗	*

Table IV.5: Linear regressions models computed to explain the annual herbicide losses by leaching observed. The significance levels retained are: *** <0.001, ** <0.01, *<0.05. The meaning of the relationship is indicated with ↗ (positive) and ↘ (negative). The relative importance of the applied herbicide quantity is indicated with a percentage. Molecules in italics are the ones from which the residuals do not follow a normal distribution.

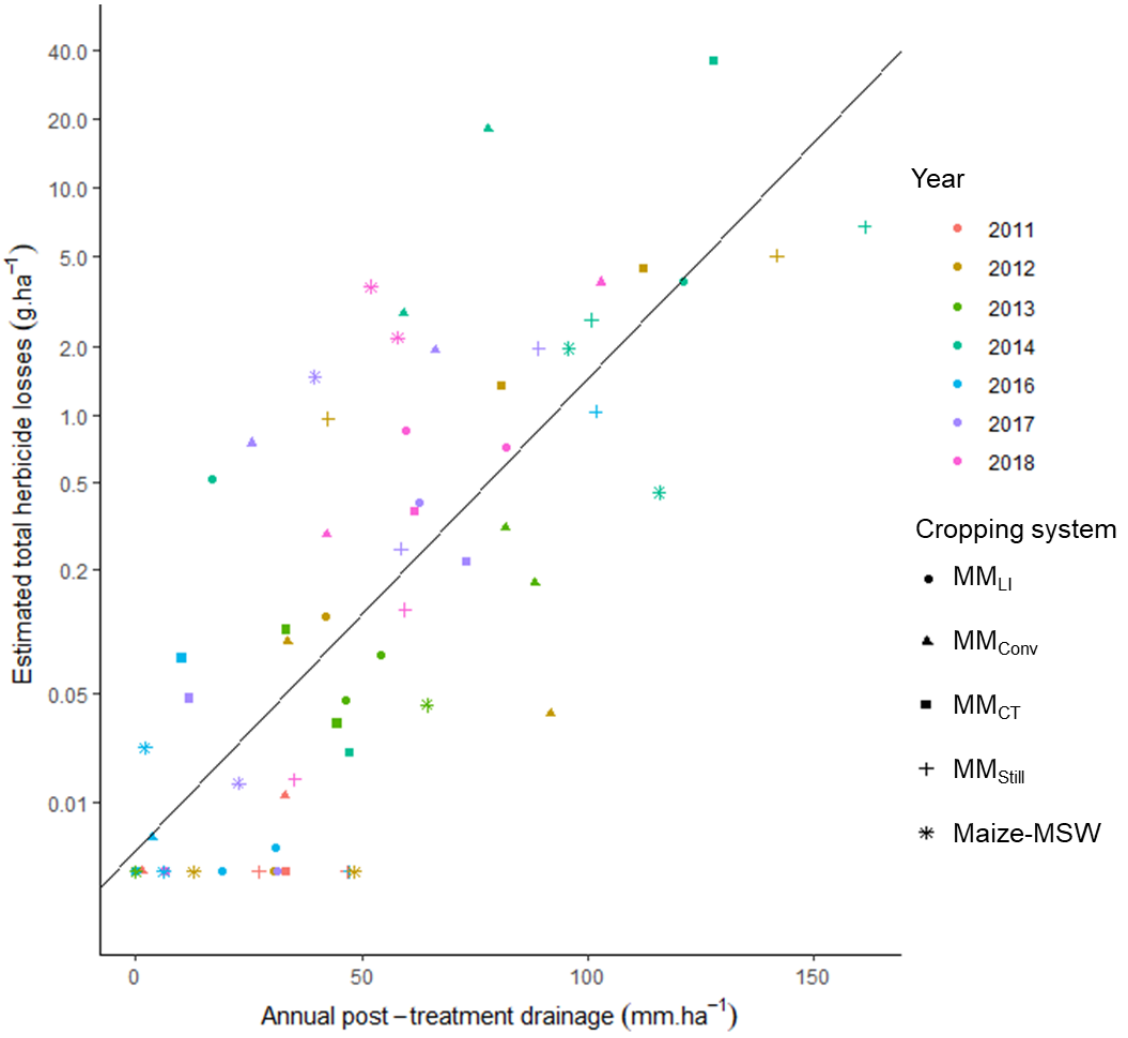


Figure IV.5: Regression of the influence of total annual drainage (after herbicide application) by estimated losses in herbicides by leaching. Note that the y-axis is logarithmic.

a) Effect of year and interaction with cropping system

Across all CS and years, mean annual herbicide losses were 1.5 ± 4.9 g ha^{-1} $year^{-1}$ and represented in average 1.2% of the total of herbicides applied (supplementary material n°2). Important differences appeared between years: 2014 experienced significantly (Kruskal-Wallis test, $p<0.05$) higher losses (7.3 ± 11.4 g ha^{-1}) than 2011, 2013 and 2016, ranging from 0.0 ± 0.0 to 0.1 ± 0.3 g ha^{-1}. 2017 and 2018 losses were intermediate between 2014 and 2011/2013/2016. In 2014, estimated losses by leaching represented up to 18.5% and 15.4% of the applied dose in MM_{CT} for nicosulfuron and mesotrione, respectively. In MM_{Conv}, they accounted for 3.7%, 1.2% and 2.9% of the nicosulfuron, mesotrione and dicamba applied doses, respectively. Finally, they represented 4.2% of the nicosulfuron applied dose in MM_{Still}. For MM_{LI} and Maize-MSW, the losses remained under 0.7% of applied dose for all years and molecules, except for Maize-MSW in 2018 where mesotrione losses represented 3.2% of the applied dose (supplementary material n°2).

b) Effect of the applied quantity

The annual dataset indicated a positive and significant influence of the applied quantity on the total losses by leaching for all molecules except mesotrione (Table IV.5). For dicamba, this applied quantity was the main variable (relative importance of 73%) that significantly influenced losses but the adjusted R^2 of the model was low (0.09). For glyphosate+AMPA and S-metolachlor, the adjusted R^2 was higher (0.39 and 0.23, respectively) but applied quantity had lower importance (relative importance of 43% and 33%, respectively).

c) Effect of cropping system

CS was not a significant variable to explain annual herbicide losses. They were 0.5 ± 1.0 g ha^{-1} in MM_{LI}, 0.7±1.2 g ha^{-1} in Maize-MSW, 1.3±2.1 g ha^{-1} in MM_{Still}, 2.0±4.8 g ha^{-1} in MM_{Conv} and 3.0 ± 9.6 g ha^{-1} in MM_{CT} but not statistically different. MM_{CT} had the highest mean herbicide losses but had the lowest third quartile (0.4 g ha^{-1}). Otherwise, MM_{CT} needed only 1.5 drainage events to reach 90% of the total losses. In comparison, Maize-MSW needed 2.0, MM_{LI} 2.5, MM_{Conv} 3.5 and MM_{Still} 6.0 drainage events to reach 90% of the total losses. The initial objective to reduce herbicide losses by 70% with respect to MM_{Conv} (2.0 ± 4.8 g ha^{-1}) was reached for MM_{LI} (-73%) and almost achieved for Maize-MSW (-65%). MM_{LI} and Maize-MSW also had a more limited herbicide losses variability with standard deviations of 1.0 g ha^{-1} and 1.2 g ha^{-1}, respectively (Figure IV.6.b).

The reduction of herbicide losses was similar to the reduction of applied herbicide quantity in MM_{LI} (-63%) and Maize-MSW (-67%). However, the relationship between herbicide leaching and herbicide application was absent molecule by molecule (Figure 6.a and 6.b) or year by year (supplementary material n°2). Compared to MM_{Conv}, losses registered in MM_{CT} were 50% greater, while the applied herbicide quantity was +17%. Finally, MM_{Still} applied 7% more herbicide compared with MM_{Conv} but it reduced the losses by 34%. MM_{Still} (0.63 ± 1.37 g ha^{-1}) and MM_{Conv} (0.24 ± 0.71 g ha^{-1}) nicosulfuron annual losses were significantly higher ($p<0.1$) than MM_{LI} (0.01 ± 0.02 g ha^{-1}) and Maize-MSW (0.00 ± 0.00 g ha^{-1}). Mean annual ESA+OXA

losses (2016-2018) across all CS was 3.99 g ha^{-1} while the S-metolachlor losses recorded on the same plots was 0.73 g ha^{-1}. ESA+OXA losses were also very variable with a maximum of losses in 2018 in MM_{Conv} (15.1 g ha^{-1}). MM_{LI} also registered important losses some year (11.3 g ha^{-1} in 2017).

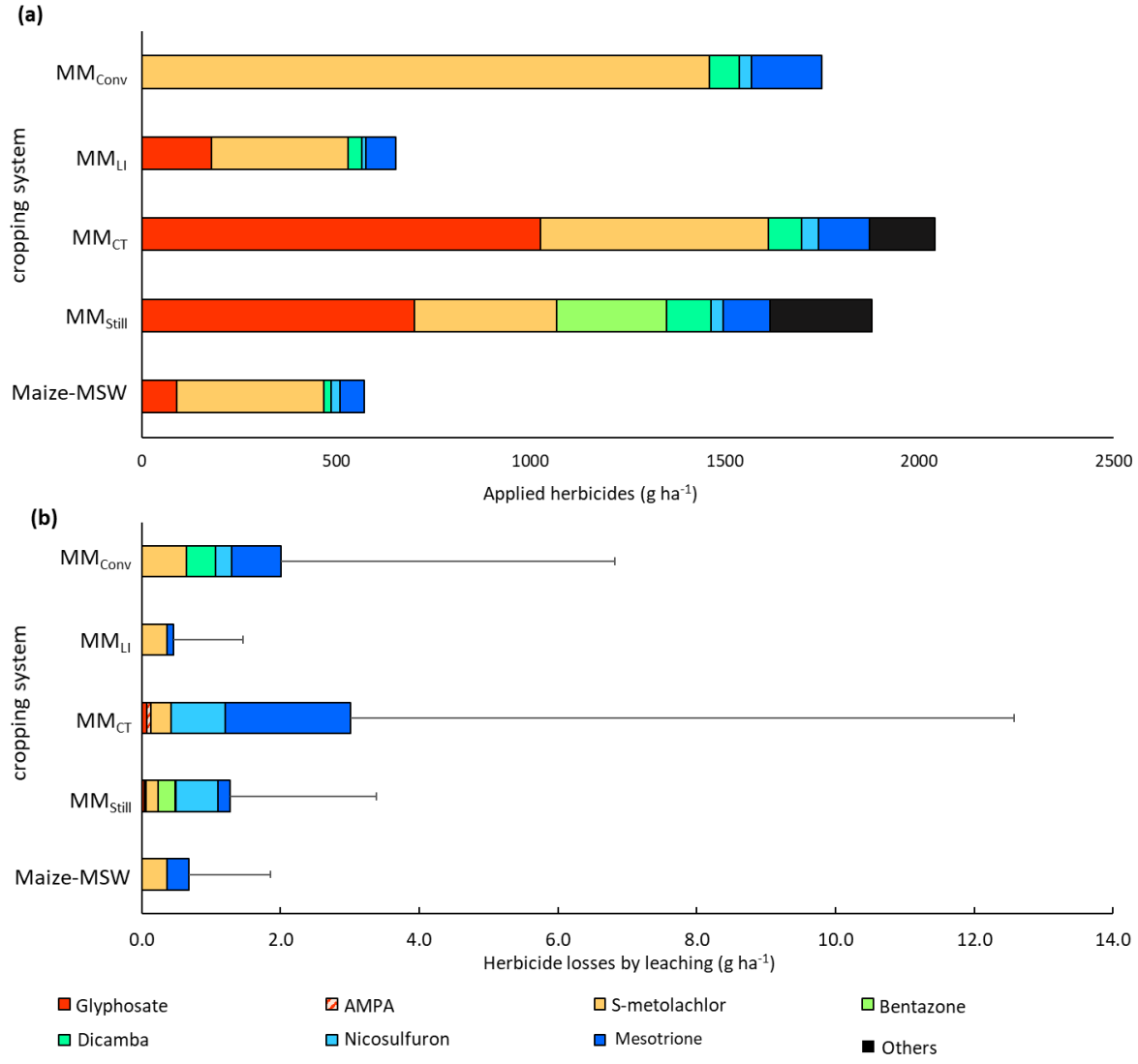


Figure IV.6: Mean annual applied herbicide amounts (a) and herbicide losses by leaching (b) per cropping system on the 2011-2018 period (g ha-1). Error bars represent standard deviation (SD).

IV. Discussion

Out of a total of 130 samples collected, 102 had an herbicide concentration under 5 µg L^{-1}, that is the raw water norm. The highest concentrations measured were on mesotrione (29.0 µg L^{-1}) and nicosulfuron (12.8 µg L^{-1}), both in MM_{CT}. Detection frequencies by molecule ranged from 31% (dicamba) to 89% (S-metolachlor). These frequencies are higher than the ones observed in southwestern France rivers and watersheds where herbicide detection varies from 5% to 50% (AEAG, 2015). These lower detection rates at regional scale can be explained by a time dilution because monitoring lasted throughout the year in AEAG (2015) while it was restricted to the maize growing season here. There was also a space dilution since all land does not contribute to water pollution: in southwestern France, grain production only accounts for 15% of the total regional territory (CRAO, 2016).

1. What influences herbicide leaching in cropping systems?

When bentazone (*n*=6) was excluded, individual models of herbicide leaching were moderately explicative of the variations of concentrations (adjusted R^2 ranging from 0.17 to 0.52) and losses (adjusted R^2 ranging from 0.25 to 0.57). Adjusted R^2 indicate that an important part of the experimental results remained unexplained, probably due to the complexity of water and solute dynamics, which was already illustrated by a comparison model approach in MM_{CT} from 2011-2013 (Marín-Benito et al., 2014).

a) Drainage regulation: linking quantitative and qualitative water management

Despite this uncertainty, there was clear evidence that drainage volume was a consistent factor that governed herbicide losses across all CS studied. No dilution effect was detected since, for almost all the variables measured (*i.e.*, concentrations and losses for most of the molecules, on individual and annual data) were related to drainage volume, from 5% to 48% for the concentrations and from 12% to 61% for the losses.

Herbicide leaching was thus influenced by annual water regime. For example, 2014 losses were very high because of intensive rain events that occurred after early season irrigations. Unfortunately, the presence of the groundwater above the lysimeter plates did not permit monitoring the fate of herbicide leaching in a rainy post-treatment period (2013) and also during winter, a season when molecule – and especially metabolite – concentrations can increase with the reduction of ascendant water fluxes in the soil profile (Agnan et al., 2019).

High volume leachates tended to be the most concentrated. After eight years of experiments, 90% of the losses registered in each CS were only due to very few drainage events (from 1.5 to 6.0). The link between herbicide concentration and drainage volume suggests that quantitative and qualitative water management need to be considered simultaneously. Two cropping practices need thus to be particularly considered:

iii. Irrigation management is a primordial element influencing herbicide fate (Lopez-Pineiro et al., 2017). The use of tensiometers or soil humidity probes to pilot irrigation can avoid

irrigation excesses that can lead to drainage. In this study, reduction of the coverage of crop water needs at 90% of the maximal evapotranspiration combined with the use of earlier maturing maize varieties reduced the number of drainage events in MM_{LI} (2.6 ± 1.6) and Maize-MSW (3.1 ± 2.1) compared with MM_{Conv} (4.7 ± 2.2). Optimization of irrigation can thus reduce the risk of herbicide transfer to water. In the future, reduction of the coverage of crop water needs could be further considered if adequate techniques and tools (*e.g.*, mulching, drought-tolerant varieties) are developed to maintain overall CS performance.

iv. Introduction of a winter cover crop before maize can be a relevant option to reduce i) drainage water during the fallow period (-30 mm on average) and ii) soil water content at maize sowing (Meyer et al., 2019). MM_{Conv}, the only CS without cover crop, had the most drainage events. Drainage reductions in the early season could limit herbicide leaching when most herbicide applications occur and leaching risk is important. Indeed, this study confirms the existing literature (*e.g.* Anyusheva et al., 2016; Masters et al., 2013) on the importance of DALT to explain individual concentrations for bentazone (relative importance of 86%), mesotrione (62%), S-metolachlor (48%) and nicosulfuron (20%). Moreover, laboratory studies using similar cover crop mulches to this experiment showed that glyphosate could rapidly bind to residues left at the soil surface in reduced tillage CS (Cassigneul et al., 2016). Finally, cover crops may have other beneficial effects on SOC (Poeplau and Don, 2015), weed management (Smith et al., 2020), that could, in the long term, permit further herbicide use reductions.

b) Molecule leaching differences – influence of physicochemical properties

The physicochemical properties of the molecules also contributed to explain the differences in concentration and losses observed for each molecule. Glyphosate, AMPA, and dicamba, three molecules considered ‘low leachable’ by PPDB (2020) had very low frequencies of leachates with concentration above 1 µg L^{-1} (respectively 5%, 0% and 3%), whereas, bentazone and nicosulfuron, considered ‘high leachable’, had respectively 67% and 18% frequencies of leachates above 1 µg L^{-1} (Table 1). However, mesotrione and S-metolachlor, considered respectively with ‘low leachability’ and ‘transition state’ by PPDB (2020), had 20% and 36% frequencies of leachates with concentration above 1 µg L^{-1} as well as high maximum concentrations. This result indicates that each molecule fate and leaching risk assessment has to be considered in relation to its context use: soil characteristics and cropping management.

Compared with other studies, some molecules were less detected and quantified: annual S-metolachlor losses never exceeded 0.42% of the estimated applied dose (supplementary material n°2) while it reached up to 2% in several field scale studies (Alletto et al., 2010). However, considering ESA and OXA in further studies on S-metolachlor will be necessary since their annual losses were, on average, 7 times higher than S-metolachlor.

In two studies comparing several maize herbicides including S-metolachlor and mesotrione (Milan et al. (2015) and Agnan et al. (2019)), much higher concentrations of S-metolachlor than mesotrione were measured, which is inconsistent with our results. However, in Milan et al. (2015) artificial rain was simulated to generate drainage with very low DALT (from 1 to 28). In the present study, only 11 samples for mesotrione and 6 samples for S-metolachlor had

DALT<28 because water dynamic was not stimulated by artificial rain. In Agnan et al. (2019), soils were less clayey, and sampling was done at 50-cm depth with ceramic cups put in depression from -600 to -800 cm, 6 to 8 times higher than in the present study. The high concentration of mesotrione recorded in this study could be explained because its sorption on soil colloids was prevented by intensive rain events, as emphasized in a recent laboratory study (Cueff et al., 2020).

If studies in field conditions are rare, in particular for mesotrione and nicosulfuron, this study fits with existing literature for other molecules. Hall and Mumma (1994) registered dicamba losses by leaching comprised between 0.0% to 5.6% of the estimated applied dose while they varied from 0.0% to 2.9% in the present study. However, Hall and Mumma (1994) reported different results because their conventional tillage CS resulted in more losses than their conservation tillage CS. As Fomsgaard et al. (2002), concentrations of glyphosate and AMPA were low and represented 0.00% to 0.06% of the applied glyphosate dose, which is consistent with the main transport process of these molecules by runoff and erosion due to their high Koc.

c) Soil and tillage influence

Even though soil composition (clay content, SOC, pH) is known to influence herbicide leaching (Gonzalez et al., 2010), soil composition had overall low influence in this study. Soil composition had a relative low variability among plots and thus had limited influence. Nevertheless, the significant and positive correlation between pH and dicamba leachate concentration is consistent with the literature (Azejjel et al., 2008).

Pesticide fate is influenced by soil structure, which in turn is modified by cultural practices. Here, glyphosate was detected almost as much as AMPA (39% vs 47%) and with similar concentrations (average of 0.12 µg L^{-1} versus 0.09 µg L^{-1}) in reduced tillage CS. These relatively important glyphosate frequencies and concentrations were surprising and could be explained by i) a slower degradation of the molecule than estimated according to its degradation half-life values (5 leachates collected after DALT>100) and ii) macroporal preferential flows illustrated with two leachates containing glyphosate at 0.38 µg L^{-1} and 1.22 µg L^{-1} after only 5 and 15 DALT, respectively. This second point is supported by the literature (Cueff et al., 2020; Zhu et al., 2020), by important mesotrione concentrations recorded with low DALT (e.g. 29.0 µg L^{-1} at 6 DALT in 2014 in MM_{CT}) and, furthermore, by the detection of early peaks (2.7 µg L^{-1} of mesotrione at 11 DALT in 2012 in MM_{CT}; 1.22 µg L^{-1} of glyphosate at 15 DALT in 2016 in Maize-MSW) for molecules never applied before on these plots.

These macroporal preferential flows could have been present in ploughing CS (*e.g.* total herbicide concentrations of 11.3 µg L^{-1} at 22 DALT in MM_{Conv} or 4.69 µg L^{-1} at 37 DALT in Maize-MSW) but may have been detrimental in reduced tillage CS. Higher pesticide leaching under conservation tillage, linked with preferential flows, was reported in previous studies (Dairon et al., 2017; Reichenberger et al., 2007). Intensive rain events occurring on soils with an increased number of macropores and a higher pore network connectivity led to voluminous and highly concentrated leachates. Preferential flows probably occurred in 2014 (supplementary material n°2) in this study and were responsible for the losses in MM_{CT} especially because this CS also increased its use of herbicides and only slightly reduced irrigation water with respect to MM_{Conv}.

d) Cropping practices

The present study is one of the few that compares several herbicides leaching in contrasted long term CS. These CS were designed to reduce the use of herbicides, assuming that this reduction will moderate their negative impact on the environment (Pelosi et al., 2017), that was partly confirmed with STICS-MACRO modelling on the experimental site of the present study (Lammoglia et al., 2017).

Molecules, doses and timing of application, identified by Reichenberger et al. (2007) as the main levers available to reduce pesticide leaching, were adapted for each CS according to their soil and weed flora conditions. The present study only partly confirms those levers: four out of six herbicide molecules losses were influenced from 4% to 17% by the applied quantity (Table 5). The choice of the molecule was also important since some molecules leached more than others in respect to their dose applied (Figure 6, supplementary material n°1).

Despite the high variability and the low statistical power of the experiment, CS approach was accurate to deal with herbicide leaching reduction. Two agroecological CS, MM_{LI} and Maize-MSW, more than halved their herbicide leaching with respect to MM_{Conv}. These CS combined a set of agroecological levers that helped to reduce macroporal preferential flow and impact on water quality: irrigation reduction, earlier maturing varieties, cover crop introduction, herbicide rate reduction, later and/or localised herbicide application and a moderate to intensive soil tillage. This approach is similar to the "many little hammers" ecological approach, originally developed to manage crop-weed interactions (Westerman et al., 2005). Despite diverse processes, every aspect of a CS influences herbicide leaching, as was reported for weed dynamics. When combined properly, these "little hammers" can reduce herbicide leaching through drainage limitation, and enhanced herbicide retention and degradation.

Nevertheless, even the combination of agroecological levers cannot result in a total absence of chemical pollution, as emphasized by the average losses in MM_{LI} and Maize-MSW or important herbicide leaching peaks detected on those CS with molecules (*eg* a 21.8 µg L^{-1} total leachate concentration in Maize-MSW in September 2018) or metabolites (ESA and OXA).

2. Cropping systems multicriteria assessment (Table IV.6)

MM_{Conv} was representative of a high-input maize-based CS from southwestern France with a 229 ± 52 mm ha^{-1} irrigation compared to a 190 mm ha^{-1} regional mean (CRAO, 2016) and a 2.1 ± 0.9 HTFI, while regional means vary from 1.5 to 2.0 (Renoux, 2016). These inputs led to grain yield (11.5 ± 2.3 t ha^{-1}) similar to the regional mean (11.2 t ha^{-1}) and satisfactory weed management with low weed biomass at maize flowering. However, when HTFI was low (2011, 2016 and, especially, 2018), weed biomass was high since no other alternative weed management techniques were employed. Due to the representativeness of the CS across the region, the average annual herbicide losses (2.0 ± 4.8 g ha^{-1}) tell the magnitude of herbicide losses under this CS in the regional context.

In respect to MM_{Conv}, the objective of MM_{LI} was to reduce HTFI by 50% and irrigation by 25%. After this eight-years study, MM_{LI} had good performance since HTFI reduced by 57% (0.9 ± 0.9) and irrigation by 21% (181±38 mm ha^{-1}) compared with MM_{Conv}. MM_{LI} had significantly fewer drainage events than MM_{Conv} which probably helped to reach, along with cover crop introduction (White et al., 2009), a 73% herbicide leaching reduction (0.5 ±1.0 g ha^{-1}) for a -70% objective. Finally, MM_{LI} yielded similarly to MM_{Conv} at 10.7 ± 2.9 t ha^{-1}. Weed biomass at maize flowering was slightly higher on MM_{LI} compared with MM_{Conv}, especially in some years (*e.g.* 2017) but did not lead to a significant yield reduction, probably due to enough available resources remaining for the crop, or a high weed diversity with few dominant species such as *E. crus-galli* (Adeux et al., 2019b). This CS confirmed thus previous results, it is profitable with a good gross margin (1254 € ha^{-1}, Giuliano et al., 2016) and is a concrete example that an appropriate combination of agroecological levers can reconcile technical and environmental performance (Meissle et al., 2010).

		Grain yield (t ha^{-1})	Weed biomass at flowering (g m^{-2})	Irrigation (mm ha^{-1})	HTFI	Herbicide leaching (g ha^{-1})
MM_{Conv}	Objective (regional mean)	11.2	Low weed pressure	190	1.7	Unknown
	2011-2018 mean	11.5 ± 2.3	23 ± 31	229 ± 52	2.1 ± 0.9	2.0 ± 4.8
MM_{LI}	Initial objective	100% MM_{Conv}	100% MM_{Conv}	75% MM_{Conv}	50% MM_{Conv}	30% MM_{Conv}
	2011-2018 mean	10.7 ± 2.9	32 ± 51	181 ± 38	0.9 ± 0.9	0.5 ± 1.0
	Relative gap with the objective achievement	↘ 7%	↘ 39%	↘ 5%	↗ 14%	↗ 17%
MM_{Still}	Initial objective	90% MM_{Conv}	100% MM_{Conv}	85% MM_{Conv}	100% MM_{Conv}	50% MM_{Conv}
	2011-2018 mean	6.2 ± 4.0	80 ± 125	214 ± 51	2.6 ± 1.7	1.3 ± 2.1
	Relative gap with the objective achievement	↘ 40%	↘ 248%	↘ 10%	↘ 24%	↘ 30%
MM_{CT}	Initial objective	90% MM_{Conv}	100% MM_{Conv}	90% MM_{Conv}	100% MM_{Conv}	50% MM_{Conv}
	2011-2018 mean	7.6 ± 3.3	142 ± 217	196 ± 47	2.6 ± 1.3	3.0 ± 9.6
	Relative gap with the objective achievement	↘ 27%	↘ 517%	↗ 5%	↘ 24%	↘ 200%
Maize-MSW	Initial objective	100% MM_{Conv}	100% MM_{Conv}	75% MM_{Conv}	50% MM_{Conv}	30% MM_{Conv}
	2011-2018 mean	9.8 ± 2.2	40 ± 61	186 ± 36	1.0 ± 0.9	0.7 ± 1.2
	Relative gap with the objective achievement	↘ 15%	↘ 74%	↘ 8%	↗ 5%	↘ 17%

Relative gap with the objective achievement > 0%
0% > Relative gap with the objective achievement > ↘ 10%
↘ 10% > Relative gap with the objective achievement > ↘ 30%
↘ 30% > Relative gap with the objective achievement > ↘ 100%
↘ 100% > Relative gap with the objective achievement

Table IV.6: Multicriteria assessment of cropping systems compared with the initial objectives. HTFI is the Herbicide Treatment Frequency Index. The meaning of the relationship indicates if the objective was overwhelmed (↗) or not reached (↘). Mean ± standard deviation.

Maize-MSW had input reductions, herbicide leaching and weed biomass very similar to MM_{LI} but yielded significantly less than MM_{Conv} with 9.8 ± 2.2 t ha^{-1}. Maize-MSW was partly penalized because of a worse soil structure compared with MM_{LI}/MM_{Conv} and a flooding in Maize-MSW plots in 2013 that strongly limited yield that year (-3 to -4 t ha^{-1} as regards MM_{Conv}). Though a reduction in weed infestation was expected due to crop rotation (Fried et al., 2008), yet it was not the case here. The following hypothesis can be done: i) with respect to MM_{Conv}, this CS used much less herbicides and thus limited the beneficial effects of the rotation and, ii) with respect to MM_{LI}, both CS used agroecological levers such as mechanical weeding or cover crops to regulate weeds, practices known to be efficient in plenty of situations and not only in crop rotations (Leblanc et al., 1995; Smith et al., 2020). The combination of low HTFI and reduced irrigation seems promising to reduce drainage events and hence herbicide leaching.

Reduced tillage CS obtained poor overall results from a multicriteria perspective. Their economic margin was low (Giuliano et al., 2016) and, compared to MM_{Conv}, MM_{Still} and MM_{CT} did not manage to maintain HTFI (2.6 ± 1.7 and 2.6 ± 1.3, respectively) while weed management remained unsuccessful with high weed biomass (142 ± 217 g m^{-2}). Both years when HTFI was significantly reduced in MM_{CT} (2017 and 2018) led to the highest weed infestations that only caused a yield reduction in 2018. On the other hand, the two best years for weed control (2015 and 2016) were the years with the highest HTFI.

MM_{Still} and MM_{CT} CS yielded 30% to 40% less than MM_{Conv}: 7.6 ± 2.3 t ha^{-1} in MM_{CT} and 6.2 ± 4.0 t ha^{-1} in MM_{Still}. That result could be expected – with a lesser magnitude – in MM_{CT} but not in MM_{Still}, which was hypothesized to be a compromise between ploughing and conservation tillage. In tilled soils, although unstable and transient (Alletto et al., 2015), the macropores created by tillage often lead to good conditions for maize establishment and development. On no-till or strip tillage CS, increased aggregate stability, through carbon accumulation, and increased biological activity are needed to create porosity and compensate for the lack of tillage which implies a transition period for these properties (Strudley et al., 2008). Consequently, most of the results on unstable fine-textured soils with hydromorphic features and low organic carbon content, as those of this study, showed at best a lack of effect (Alletto et al., 2011; Fortin, 1993; Licht and Al-Kaisi, 2005b), but most often a decrease of yield under reduced tillage CS due to unfavorable germination, seeding and crop development conditions compared to conventional tillage (Drury et al., 1999; Hussain et al., 1999; Vyn and Raimbault, 1993). In an 8-years study in maize monoculture, Fiorini et al. (2020) observed only a 5% yield reduction under no tillage and a 10% yield increase on minimum tillage that consisted of a ripper followed by disk harrowing and thus had a higher tillage intensity than MM_{Still}. Compared with MM_{Conv}, annual herbicide losses by leaching reduced to 1.3 ± 2.1 g ha^{-1} in MM_{Still} while increased to 3.0 ± 9.6 g ha^{-1} in MM_{CT}. In MM_{CT}, the positive influence of cover crop introduction (Alletto et al., 2012; White et al., 2009) was not observed, maybe because the time between herbicide application and the leaching event was too short. The present study confirms herbicide leaching increase in reduced tillage CS on a wide range of molecules. This study also highlights that molecules substitution from one CS to another (from S-metolachlor in MM_{Conv} to glyphosate, mesotrione and nicosulfuron in MM_{CT}) may worsen herbicide leaching especially when HTFI is not reduced.

The reduced tillage CS, especially when implemented with soil coverage and crop rotation, were firstly adopted in regions where wind or water erosion occur. There is clear evidence that these techniques have a positive impact on erosion and runoff (*e.g.* Palm et al., 2014). However, the relevance of these CS in lowlands, where erosion is negligible, can be questioned in light of the results obtained here.

3. Considerations to evaluate cropping systems performance

The results from this study can help design and assess CS to reduce the herbicide concentration in water leaching, among other environmental impacts. The indicator used to evaluate the risk of herbicide dissipation in the environment must be chosen carefully. For example, compared to MM_{Conv}, MM_{Still} had a significantly higher HTFI (+24 %), a slight increase in applied herbicide quantity (+6 %) but an overall reduction in herbicide leaching (-35 %). In MM_{LI}, results on herbicide were all going in the same direction with reductions of 57% for HTFI, 63% for applied quantity and 73% for herbicide leaching. At the annual scale, the relationship between a management/pressure indicator (HTFI) and impact/performance indicators (herbicide leaching and weed biomass) were extremely tenuous (respective R^2=0.03; p=0.07 and R^2=0.02; p=0.2), which encourages the use of impact indicators to better assess CS designed to reduce environmental impacts. HTFI and weed biomass at flowering were poorly corelated, probably because of i) the positive impact of the alternative techniques used to replace herbicides and ii) high HTFIs do not prevent high weed biomass (Adeux et al., 2019a).

While comprehension of the processes linking pesticide application and leaching must be deepened, CS must be evaluated globally, to include grain production and weed pressure. Winter crop (wheat) introduction in the Maize-MSW rotation resulted in an annual drainage of 35.7 mm ha^{-1} *versus* 47.9 mm ha^{-1} in maize. The risk of consecutive water pollution is then lowered: low concentrations of herbicides used on winter crops were found in the water samples when their acreage was greater than maize in southwestern France (AEAG, 2015). The inclusion of winter crops in the rotation also contributes to reduction of weed pressure in maize (Adeux et al., 2017) with positive consequences for the reduction of herbicide use and leaching.

Conclusion

At the plot scale, the present study encourages consideration of herbicide – and more generally pesticide – leaching as a risk that is inherent to the use of chemicals, even when used sparingly. Because of the influence of drainage volume, quantitative and qualitative water management must be studied concomitantly. However, because very few events are responsible for most of the losses, leaching represents a risk for agroecosystems. This risk can be attenuated by integrating in CS several agroecological levers including a precise irrigation management, cover crops, early variety, tillage, herbicide use reduction. Maize-MSW and MM_{LI} combined these levers together and buffered the risk while reaching other environmental and socio-economic objectives.

At the plot scale, the management options adopted here to reduce herbicide water pollution can be completed with other practices such as agroforestry (Dollinger et al., 2019). At a larger scale, reduction of water pollution could be done with landscape infrastructures such as sown grass strips to limit runoff (Reichenberger et al., 2007).

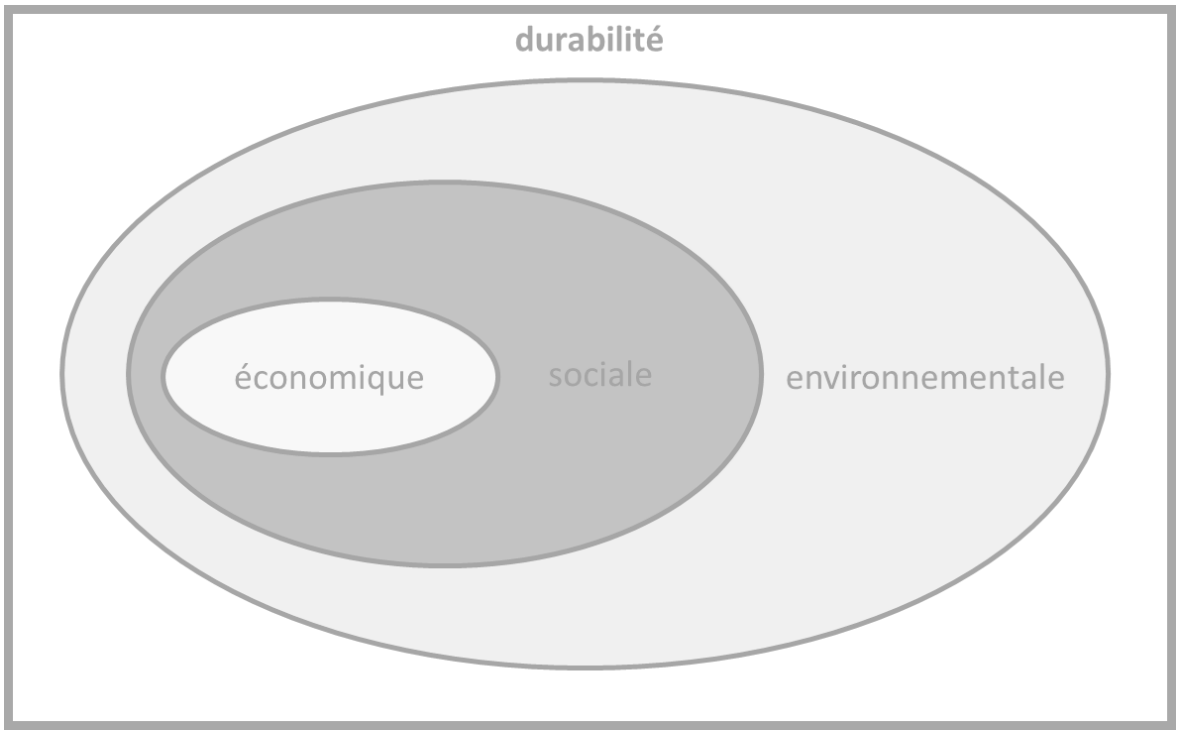
Acknowledgements

The authors would like to thank all the people involved in the fieldwork and the data collection during those eight-years, particularly Gaël Rametti and Pierre Larsonneau. The authors would like to thank Sandra Wayman for revising English language and her help to make a more straight-forward paper. Finally, the reviewers are thanked for their attentive reviews and advices that helped to improve the article.

Funding

This work was financially supported by INRAe Metaprogramme Adaptation of Agriculture and Forest to Climate Change VACCARM, ANR Systerra MICMAC-Design (ANR-09-STRA-06), by the "Conseil Régional d'Occitanie" (project no. 10051579) and by ONEMA through the SYSTEM-ECO[4] project.

Chapitre V
Discussion générale et perspectives de recherche



I. Maize based-cropping systems towards agroecology

1. Main scientific advances permitted by the thesis

Chapter I enabled to **identify the main maize-based cropping systems worldwide and their consequences on the environment**. It emphasized that maize production in the three main productive regions in north-hemisphere, US, China and Europe have a similar pattern, despite regional differences occur. First, in these cropping systems, maize is cultivated mainly in very short rotations of one or two years. The main elements that stand out of MBCS in these zones are their high use in nitrogen (from 140 to 350 kg ha^{-1}), their intensive tillage – with the exception of the conservation tillage cropping systems spreading in the US – and their systematic use of pesticides. That dominance of maize in the rotations along with the important use of external inputs make that cropping system very sensitive to the global market. Moreover, technical management of the MBCS implies negative impacts on the environment, including water pollution by nitrate and herbicide and soil decay (erosion, reduced quality and biodiversity). The technical solutions, including tillage reduction, cover crops, crop diversification or varietal changes, developed by research to reduce these impacts are promising but are mostly studied *ceteris paribus* which unlikely to take advantage of the beneficial interactions between techniques. Entire cropping systems studies could permit to obtain better results on all cropping systems outputs (economy, environment, and labour).

The work conducted in chapters II, III and IV contains **the first most important methodological improvements** which is the **field experimentation, evaluation, and comparisons of entire cropping systems.** Unlike in most of the studies that are focused on the evaluation of several options of a single agricultural practice (fertilization, tillage or cover crop), all the MBCS experimented in these studies are entire cropping systems with specific decision rules to manage them according to their objectives.

More specifically, chapter II offers a first and most integrative approach of the **second major thesis contribution** which is the **multicriteria assessment of the cropping systems, based on quantitative and experimental data.** In that chapter, a multicriteria quantitative experimental assessment of three innovative cropping systems and comparison with a MBCS reference in southwestern France is done. The alternative CS tested were built to benefit from the interaction between practices such as conservation tillage with cover crops, herbicide application on the row crop with interrow cultivation or earlier varieties and irrigation reduction. Good multicriteria performances were obtained by MBCS that combined agronomical levers and maintained ploughing while the conservation tillage MBCS resulted in poor environmental and economical performances.

Finally, chapters III and IV bring the **third main scientific advance** of the thesis through the **quantification of cropping system impact based on *in situ* measurement.** Since these measurements are made further on the causal chain in respect with the more traditional pressure quantification (herbicide load per hectare, number of mechanical weeding…), they can identify more precisely the ongoing processes in the MBCS and evaluate their impacts.

Chapter III was then developed to **understand how weed flora evolved in the different cropping systems and more specifically why reduced yield was obtained on the conservation tillage CS**. Chapter III reveals that herbicides were more often used on the conventional and conservation tillage MBCS. It also shows that **weed community shifted differently between the MBCS**. Conservation tillage MBCS was affected by higher grasses and perennial species than the ploughed MBCS. Nevertheless, if weeds had a negative impact on maize yields on all the MBCS, they couldn't stand alone as responsible for yield reduction on conservation tillage MBCS. Indeed, maize yield on weed free zones on the conservation tillage system was reduced in respect with the yields on weed free zones on ploughed systems.

Chapter IV allows then to deepen the **impact of the herbicides on drainage water on the various MBCS tested**. It confirms, on an 8-year period, that both conservation tillage CS and conventional CS used more herbicides than IWM MBCS. That chapters shows that the MBCS that used more herbicides were the ones that had more losses of herbicides in drainage water, despite these losses were not proportional to the amount applied. That chapter also reveals that **very few drainage events can be responsible for most of the losses**, which can be explained by preferential fluxes, hypothesized to be more present in conservation tillage MBCS since any soil disturbance occurs to undo the biomacroporosity that developed under these reduced tillage managements. Finally, that chapter shows that herbicide losses recorded are mainly linked with the amount of water lost by drainage. That result encourages research and agricultural sector to manage concomitantly water quality and quantity at the plot level, notably by reducing the use of herbicides, especially in frequency, and by reducing the risk of leaching mainly with cover crops integration and irrigation management.

Considering the whole work conducted, **the present thesis contributes to increase knowledge about how a high-input cropping system such as an irrigated maize monoculture can improve its environmental performances while maintaining or improving the economic profitability**.

However, the approach conducted in the present studies reveals some limits to extend more broadly the conclusions. The range of the alternative MBCS cropped on the Lamothe long term cropping system experiment remains narrow, from three different monocultures reducing the use of some inputs (herbicides, irrigation water, mineral nitrogen and/or tillage) to an IWM 3-year rotation. For the moment, the experimental device does not include a « true » conservation agriculture MBCS that would include a diversification of the crops in the rotation in addition to soil coverage and a minimum tillage that are both already present in MM_{SD}, and, to a certain extent, in MM_{Still}. To undo that limit, a conservation agriculture MBCS was designed during a co-design workshop in spring of 2023 and then will be field-tested by the autumn. To widen the MBCS tested, the experiment also included from 2018 an organic agriculture MBCS that will be interesting to evaluate in next years. A future challenge on this experiment will be to evaluate entirely the IWM 3-year rotation and not only the maize included in that rotation.

Furthermore, to understand better the impacts of MBCS on the weed dynamics or on herbicide leaching, complementary experiments or measurements could be done, to understand better the process underlying the performances measured. For example, the study conducted by (Alletto et al., 2015) confirmed, with soil measures and a simulation evidence, the saturated conductivity shrink across the cropping season of MM_{Conv}. Other soil conductivity measures could be done in alternative MBCS to understand better the results presented in the chapter IV. Continuing

with weed free areas, including no weeded areas would be interesting to measure, respectively, the impact of weeds on yield and to measure the ability of MBCS to manage weed flora. Measuring soil seedbank would also be interesting to understand better the weed communities evolutions (Mahé et al., 2021).

2. Contribution to agroecological transition of cropping systems

The alternative MBCS tested contribute to the implementation of agroecological transition of MBCS and improve their performances. The alternative MBCS are indeed related with two key principles identified by Duru et al. (2015a and 2015b) to implement agroecological transitions at field level : diversity and state of slow variables. These MBCS increased the cultivated plant diversity (crops, cover crops) and uncultivated plant diversity as weeds (chapter III) and also probably micro-organisms diversity as revealed by enzymatic analysis made in 2021 on the experiment. The alternative MBCS also reduced the chemical (MM_{LI}, Maize-MSW) or mechanical (MM_{CT}, MM_{Still}) disturbances of the soil, that might improve soil state in the long term. The designed and tested alternative MBCS also applied the field principles identified by Wezel et al. (2020) for the transition towards sustainable food systems through agroecology with nutrient recycling with the cover crop introduction and a synthetic input reduction allowed by the integration of several levers such as mechanical weeding, an increased soil health (data not yet valorised) and potential better synergies between components of the agroecosystems allowed notably by the integration of leguminous cover crops. As a consequence of the adoption of agroecological management, ecosystem services delivery was improved, as shown for water quality (chapter IV). Same conclusion was done by other authors for different cropping systems (Boeraeve et al., 2020; Dardonville et al., 2022). The state of slow variables like organic matter is also improving under these systems, especially for MM_{CT} and MM_{CTOM} (data not published yet) which is favourable for the evolution of fast variables (*e.g.* yield) in the next years.

However, not all the cropping systems were promising on all dimensions. Both conservation tillage MBCS, MM_{CT}, MM_{Still} obtained overall poor economical results and had some low environmental performances such as an important herbicide use. That result shows that not all the transition pathways (here, basically IWM and conservation tillage) always result in better cropping system performances: an accurate combination of levers, technically mastered and adapted to the environmental context is necessary.

II. A necessary change of the co-design MBCS framework

1. In the objectives: production of ecosystem services to mitigate and adapt to climate change

a) Production of ecosystem services

Ecosystem services (ES), that can be defined as "the contributions that ecosystems make to human well-being" (Kumar, 2012), are a concept more and more used in agroecosystems, despite that notion is still debated between an ecological and a socio-economical approach (Therond et al., 2017b). ES are classified in provisioning (food, feed, fiber, biofuels…), regulating (water cycle, soil…) and cultural services. Supporting services (*e.g.* nitrogen cycling), sometimes presented in the literature as ecosystem services *per se*, are considered here as an ecological function necessary to provide regulating (*e.g.* water quality) or provisioning (*e.g.* crop quality through a high protein content) services. Differently than in "natural" ecosystems, the ES produced in agroecosystems are co-produced by natural processes and the people that crops the land. Thus, the way an agroecosystem is managed will hugely influence the level of ecosystem services produced.

As agroecology aims at benefiting from ES to manage cropping systems (Boeraeve et al., 2020), it would be necessary to be able to measure these ES. Quantification of ES is complementary with the "environmental impacts" measurements as the improvement of ES is a way to reduce environmental impacts (Soulé, 2022). Environmental impacts of two cropping systems might be identical despite different pressure levels (*e.g.* pesticide load per hectare) indicating that one of the two cropping systems has a higher level of ecosystem services (Therond et al., 2017b). In figure V.1, the agroecosystem cropped with MBCS A produces an important amount of mineral N available for the crop (ES) but the agroecosystem as a limited use of N, inducing losses in the environment. Despite higher environmental losses, in situation B, the agroecosystem provides less mineral N but its use is higher than in situation A. Knowing these characteristics, it would be possible to design an alternative cropping system combining A and B practices that produces the level of mineral N permitted by situation A and uses so much mineral N as in situation B. Note that in that last case, both external resources use and environmental impacts are minimized while ES are enhanced. More generally, disentangling ecosystem services from impacts is an important research question to focus on (Soulé, 2022).

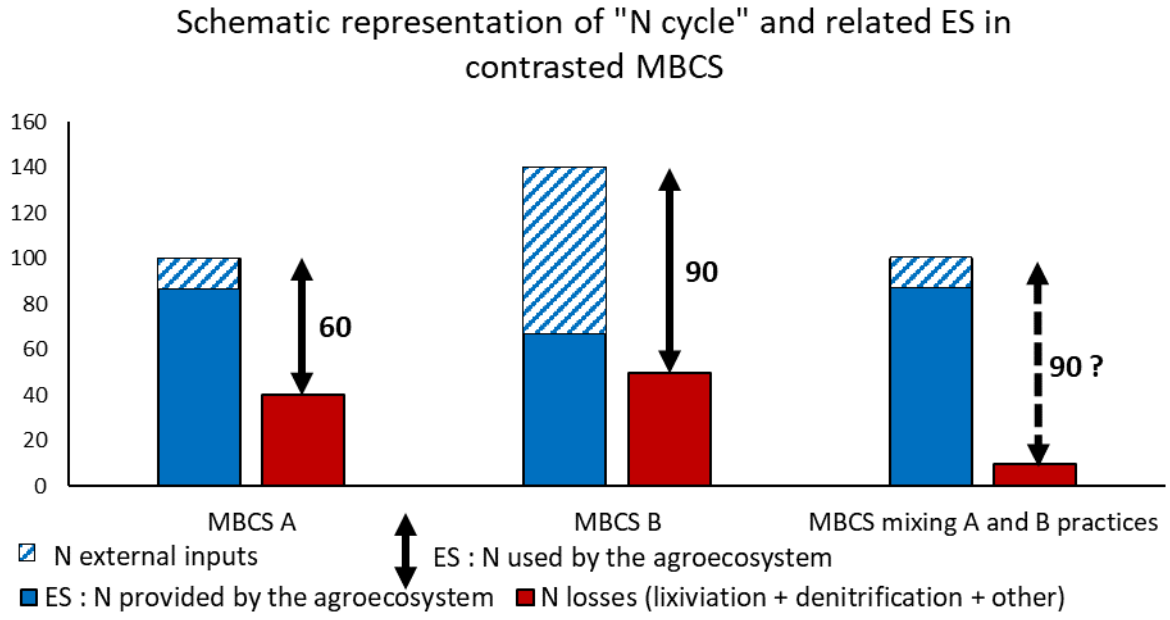


Figure V.1: Schematic representation of "N cycle" and related ecosystem services in contrasted MBCS

Therond *et al.* (2017b) identified the main biophysical determinants of the ES production in agroecosystems: the plants (crops, cover crops, weeds…) managed on the land, predators of crop pests, the landscape matrix and then three parameters related to the soil (soil organic matter, micro-organisms and macro and mesofauna). Improving these biophysical determinants should become an objective of MBCS management as a way to maximise the MBCS ES, adapted to the territory stakes, that should become the main research question to focus on. The context of climate change induces an important variability in MBCS performances thus some ES should be of particularly interest such as: climate mitigation, especially from biomass production, and water preservation.

b) Climate mitigation

In the context of environmental degradation and biodiversity crisis, MBCS sustainability should continue to consider input (pesticides, fertilizers, fuel) use, environmental impacts (*e.g.* water quality) but also need to include climate mitigation in their objectives by reducing GHG emissions, especially through biomass production. Indeed, net primary productivity is the first factor influencing the amount of carbon stored in the soil (Autret et al., 2016; Martin et al., 2021). Therefore, an increase in net primary productivity of agroecosystems is susceptible to increase soil organic carbon if the production of stable organic carbon is higher than soil carbon mineralisation.

Agroecological transition of CS needs to restore the amount of soil organic carbon since it is a major indicator related to environmental performances (Therond et al., 2017b). It allows a better soil structure, an increased water retention and water infiltration, an increased mineral availability (*e.g.* Komatsuzaki and Ohta, 2007; Plaza-Bonilla et al., 2015). It can also lead to a better crop productivity despite this is very depending on the crop management (Abdalla et al., 2019). To improve soil organic carbon in croplands and mitigate GHG emissions, future agroecological CS will have to manage concomitantly (Komatsuzaki and Ohta, 2007; Plaza-Bonilla et al., 2015):

- Net primary production and biomass return to the soil
- GHG emissions generated by the production, mainly through fuel use, nitrogen application and irrigation at field scale
- Humification coefficient of the organic matter inputs
- Soil and soil organic carbon losses through erosion and mineralization
- Level of soil carbon saturation

Biomass production and return to the soil

Cover crops are an important tool to increase biomass production and biomass return to the soil. It increases the time with photosynthesis throughout the year and biomass produced is not exported from the field and carbon produced would be sequestered for long term in soil (Poeplau and Don, 2015). Multiple species are available but mixtures with legumes and non-legumes species are known to be the ones with the best effect on crop productivity (Abdalla et al., 2019). Relay cover-crops might be of particular interest to amplify the green soil cover and productivity (Tanveer et al., 2017), especially for MBCS that are lately harvested that have limited potential for autumn cover crops growth (Alletto et al., 2022a; Giuliano, 2016). Introduction of a living mulch into maize crops can also be interesting for biomass production and brings also an interesting weed control but they have to be managed carefully not to limit crop yield because of an intense primary competition (Bhaskar et al., 2021; Lu et al., 2000). Double-cropping could also be another possibility to increase biomass production but it has to be managed carefully in order to limit the use of irrigation water and synthetic inputs (Kong, 2014).

Despite few crops produce as much biomass as maize, increased biomass returns to the soil and humification into the soil might be achieved through crop rotation. Indeed, crop rotation enhances photosynthesis with longer periods of soil coverage in respect with conventional MBCS. Moreover, the introduction of winter cereals in rotations would be beneficial for soil organic carbon as they bring back abundant carbon-rich residues to the soil if straw residue is not exported (Clivot et al., 2019) especially since wheat-derived carbon is more stable in the soil in than maize-derived carbon (Kan et al., 2022). Integration of pulses in rotations might also be interesting to increase soil organic carbon (K. Liu et al., 2020).

As global warming is likely to induce a reduction in biomass production because of drought increase (Brisson and Levrault, 2012), other ways to improve biomass production with limited inputs would be the introduction in the rotation of species more drought tolerant such as sorghum. Development of maize and cover crop varieties that require less input (water and nitrogen) and adapted to the local context and to the technical management to produce high biomass in the farmers conditions' are also needed (Wayman et al., 2017).

Including trees in agroecosystems through hedges or in field agroforestry might be beneficial for soil organic carbon. MBCS agroforestry benefits on biomass productivity and soil organic carbon content were already emphasized in Africa (Ketema and Yimer, 2014) but little research was published in the main maize production zones. (Z. Liu et al., 2020) shown that adaptation of cultivation and in particular irrigation systems must be done to achieve good performances of maize production under agroforestry.

Finally, an alternative to biomass production to increase soil organic carbon content is to bury livestock manure with important carbon content. However, that carbon source coming from animal breeding, might have a detrimental carbon footprint (Ghosh et al., 2020) and the

distribution of cattle on the territories might limit the relevance of that practice. An alternative compost origin comes from the green waste compost in urban areas. Using this type of compost on agricultural land remains challenging because of its collection and availability and also the risk to contain heavy metals and antibiotics (Wang et al., 2018), and uncertainties also exist in respect with its carbon foodprint (Ye et al., 2023).

GHG-emissions

A challenge for agroecological CS will be to produce biomass with less fossil fuels derived inputs. Since N fertilization, through CO_2 emissions for their fabrication and N_2O emissions generated by the denitrification process after their spread (see chapter I), represents the largest part of the GHG emissions of MBCS, progress will need to be achieved on N maize nutrition. Introduction of legumes species as crops and cover crops is, here again, necessary. Tillage – and especially ploughing – reduction will also be needed. Irrigation, as it increases CO_2 emissions from organic matter mineralisation, will have to be better regulated. Finally, earlier varieties with good productivity are also sought since they could reduce water and nitrogen demand and, in the same time, being harvested drier, they will need less post-harvest drying that emits important CO_2 amounts.

Lastly, an important aspect to consider that can be linked to GHG-emissions, is the albedo effect of agricultural land. Albedo effect could increase by more than 4% if cover crops sowing was generalized in Europe and even more if their cultivation period was extended (Carrer et al., 2018). However, C soil accumulation because of integration of cover crops could, in the long term, reduce soil albedo and then limit the positive impact of the first years.

Humification and mineralization processes

The amount of crop residues returned to the soil and their evolution is another important parameter to consider (Christopher and Lal, 2007). The humification coefficient is under the influence of soil temperature, soil moisture, soil texture and nutrient availability. Nutrient availability management is crucial since nitrogen availability is needed to sequester carbon (Kirkby et al., 2014). It can be brought by pulses introduction in the rotation as main crops or cover crops since N availability coming from nitrogen fertilization might be detrimental for C cycle. While texture cannot be managed by farmers, soil temperature reduction by cover crops can be valuable to favour humification (Christopher and Lal, 2007). Soil temperature reduction is present during cover crop growth in fallow period – especially in spring – but also after crop termination if the mulch is maintained in surface (Yang et al., 2021).

Leguminous-based cover crop might particularly be interesting since they could achieve both a reduction of soil temperature during fallow period and an increase of N availability in soil. Enhanced presence of earthworms could also favour C sequestration, especially in rich carbon soil (Zhang et al., 2013). An enhanced humification is likely to induce a reduced mineralisation which will be again more in favour of soil organic carbon increase. The balance between both processes depends on the C:N ratio of the organic matter incorporated to the soil, the higher it is, the higher the humification will be (Nicolardot et al., 2001). In agroecosystems, organic amendment need to be balanced on the C:N to be beneficial for the mineral nutrition of the crop and bring enough carbon to the soil.

These humification and mineralization processes are highly influenced by global warming that tends to increase mineralization and reduce humification (Calame, 2020; Komatsuzaki and Ohta, 2007).

Finally, soil organic carbon losses can be reduced in limiting soil erosion, notably through an improved soil cover and reduced tillage.

Soil carbon saturation

Finally, despite all the organic amendments possible, soil carbon sequestration is not infinite and mainly depends on soil texture (Hassink and Whitmore, 1997). The level of soil carbon saturation will be necessary integrated by agricultural sectors in the next years to evaluate the capacity of a given soil to sequester C. For the moment, the great majority of the cropland worldwide (*e.g.* 94.8% in France) is unsaturated in C which supports the high potential for additional C sequestration (Martin et al., 2021).

c) Water preservation

Along with biomass and soil organic carbon considerations, the other massive challenge of MBCS in the next years will be water management (Kang et al., 2009). If the precocity of maize varieties sown by farmers is maintained or increased, needs for irrigation will likely increase (Brisson and Levrault, 2012), which might be problematic in many regions in the world where water scarcity is expected to increase.

In the case of low water availability, field management is important to reduce water needs in choosing the adapted crops, varieties and cropping practices. However, the allocation of water needs to be optimized at the territorial scale, to mediate the priority uses of water between human consumption, ecosystems, agriculture and industry and to decide where to allocate water, according to its availability. The low water availability in some maize producing territories questions the place of irrigation in MBCS. Spring, summer and autumn water stresses might also limit the objective of biomass production, for the constituting crops of the MBCS and also for the cover crops. Indeed, cover crop growth can be limited by low water availability in autumn and can also limit the water availability of next cash crops. In a context of water scarcity an early destruction of cover crops might be done (Meyer et al., 2018).

d) Climate adaptation

MBCS should have the long-term objective to mitigate climate change through carbon cycle modification in the agroecosystems. In the same time, it is also necessary to develop MBCS that adapt to climate change already in progress. The overall temperature increases and reduced water availability during crop growth imply changes in MBCS management to maintain their performances.

Maize sowing dates will probably continue to be anticipated (Figure V.2) to limit water stress in summer even if the importance of that lever, at least in Europe, might be limited because of concomitant increase in solar radiation and precipitations reduction (Brisson and Levrault, 2012).

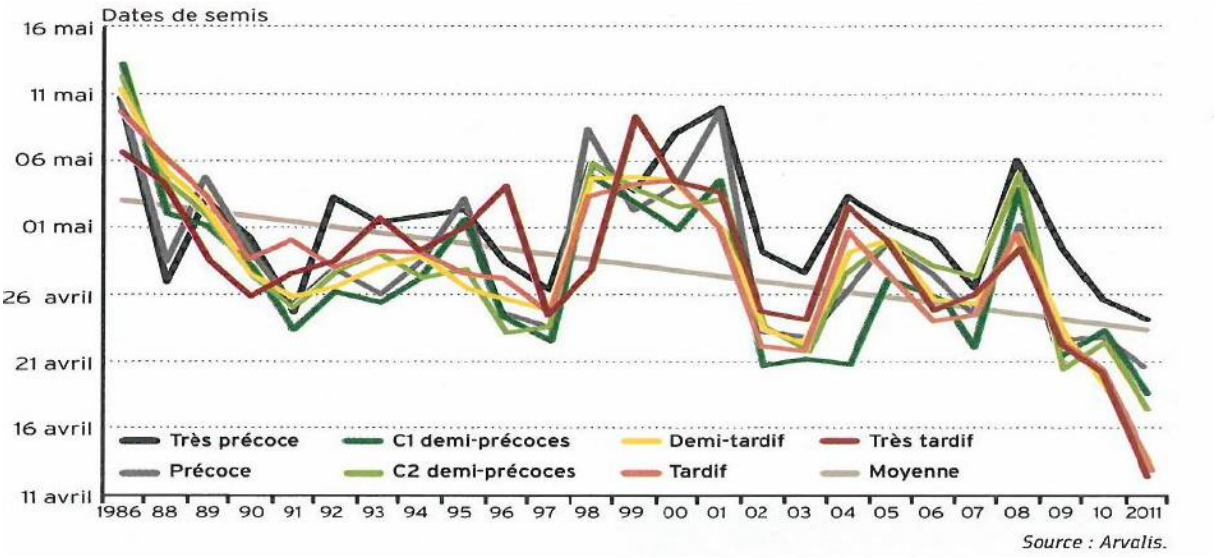


Figure V.2: Average maize sowing dates in France for varieties of different precocities between 1986 and 2011 (ARVALIS, 2012)

Varieties should also be adapted to reduce maize water demand. While later varieties might be interesting to increase maize productivity, they could have a limited performance if irrigation and water availability are reduced in summer. To face that water availability reduction, the use of earlier varieties could be interesting as an escaping strategy even if the yield potential might be reduced (Brisson and Levrault, 2012).

The most important levers to adapt to climate change might converge with the levers described for mitigation. Indeed, diversification through the introduction of new crops and cover crops into the rotation is a key to shape more resilient MBCS that will be less affected by water stresses. Winter crops, including legumes, or spring crops less water demanding such as sunflower might be good candidates to diversify MBCS and reduce their water needs.

To improve MBCS adaptation to climate change in a medium term, crop diversification and cover crop introduction might be combined with reduced tillage and introducing cover crops might improve soil water functioning and thus increase the ability for the crop to use water (Alletto et al., 2022b).

2. In the design process: adapting the co-innovation framework applied to the agroecological transition of cropping systems

a) Process organization: taking into account the collectives and the territory

Research to achieve agroecological MBCS with high biomass production and adapted to climate change is still needed. The methodological approach already developed by several authors (*e.g.* Debaeke et al., 2009; Gaba et al., 2015; Lacombe et al., 2018) needs to be enlarged according to the object considered here. To develop an innovative MBCS, co-innovation processes, already developed at farm or territory scale (Lacombe et al., 2018) or on multiple crops (Gaba et al., 2015) can be adapted to an entire cropping system, at a pluriannual scale.

To be sure that the MBCS experiment (in station or on farm) brings meaningful results and information susceptible to be useful for famers and the entire agri-food system (machinery, cooperatives, transformers, consumers), several steps must be followed. The first one is the integration of the farmers and the regional stakeholders through an open-innovation process that can take the form of a co-design approach (Jeuffroy et al., 2022; Lacombe et al., 2018; Pelzer et al., 2012). Indeed, a consequence of crop diversification or the integration of new management methods are related with higher dimensions than cropping and farming system (Boulestreau et al., 2022). For example, not all the adapted tools exist (*e.g.* to terminate a cover crop with no herbicide and no tillage) thus research and development are needed in machinery. In the same way, a farmer that would like to introduce a crop (*e.g.* a leguminous species such as lentil) that is not, for the moment, collected by the main customer of the farm necessitates at least changes in the farmer cropping system, customer organization and change in consumers' diet. To overcome those barriers, the co-design needs to be integrated in a coupled innovation process (Boulestreau et al., 2022). Coupled innovation consists in coordinating the innovation design in all the sectors that might be concerned by the innovation process (cropping system, food, distribution, machinery…) to overcome the lock-in that would be encountered if each of these systems were studied independently (Meynard et al., 2017).

That approach can be developed with workshops that include the stakeholders, in frameworks designed and leaded by researchers. However, the design is often only made by scientific experts (Colnenne-David and Dore, 2015; Giuliano, 2016) while including territorial and farms concerns, from the soil and climate aspects to the market and other socio-economic constraints and opportunities, is essential for the future adoption of the designed system. In addition, implying farmers from the beginning of the innovation process will increase their involvement and facilitate the adoption of the cropping systems designed, especially if their implication is decisional rather than observational (Lacombe et al., 2018). Farmers empowerment could be one of the result of that approach.

The design approaches proposed by Debaeke et al. (2009) or by Pelzer et al. (2020) for experimental cropping systems tested on station should be adapted and enlarged for a better adoption of agroecological MBCS in the territories:

- Step 1: building the innovation framework and fitting in a farmers' network that want to solve a problem and move towards agroecology
- Step 2: defining a consensual set of objectives, constraints, and opportunities. It is important that the objectives of the cropping system are quantified and compared with a reference cropping system that is dominant regionally. In the case of agroecological MBCS, objectives should focus on a reduction of use of inputs and on the production of ecosystem services. Note that objectives and constraints should not be too restrictive in order not to limit the innovation process.
- Step 3: co-designing agroecological CS (crops and cover crops, tillage, management) that fit the socio-economic and ecosystem services needed through the adapted decision-rules, according to the actual knowledge
- Step 4: *ex ante* evaluating the designed CS and, if needed, returning to a previous step
- Step 5: applying and/or simulating the co-designed cropping system through a range of different scenarios (climate, economy)
- Step 6: evaluating the CS in respect with the socio-economic objectives and ecosystem services fixed initially and in respect with the initial situation, the "reference system"
- Step 7: communicating the results obtained and, in regard with the results obtained, adapting the initially designed agroecological CS to fit better with the objectives or the changing constraints and opportunities (*e.g.* a new disease outbreak, herbicide withdrawal, climate change, development of a new crop market…)

However, some limitations are present in these co-innovation processes: they are time consuming, which can be problematic especially for farmers and innovation can be low if the people present in the workshop have a conservative posture.

That 7-step process is however a never-ending process. Indeed, new farmers could be included in step 1, objectives and constraints can evolve because of climate change or socio-economical change (step 2) and global and local (coming from the experiment) knowledge will also be acquired regularly, as a result of step 4 and 6. When parameters from steps 1 to 3 evolve, it should be considered to initiate a new co-design phase.

In regard with the various methodology identified by (Lacombe et al., 2018), *de novo* (co-)design seems much more applied to cropping systems while co-innovation processes tend to be more applied to entire farming systems. With the inclusion of farmers throughout the process, we assume an hybridization of these methodologies at the cropping system level. That co-innovation processes can be adapted to cropping systems if the methodology is adapted. Farmers empowerment is indeed a major factor of evolution of cropping systems and must be integrated in the innovation process.

b) How to redesign? The ESR framework enlarged to climate and agroecological stakes

Climate and ecosystem services objectives addition to the previous environmental and economic objectives of MBCS can become complex to combine and rank. How is it possible to concomitantly integrate pulse crops, systematization of cover crops, irrigation water and nitrogen reduction, conservation tillage? The Efficiency Substitution Redesign (ESR) framework (Hill and MacRae, 1996) was designed to reduce the use of pesticides in agriculture and was – for the moment – applied essentially to IPM or organic agriculture (*e.g.* Lamine, 2011; Rosati et al., 2021). Already enlarged to water management, agroforestry or conservation agriculture (Pretty et al., 2018) and to agroecology (Wezel et al., 2014), it is hugely necessary to enlarge this approach to the objective of mitigation and adaptation of climate change. For instance, the enlargement of the ESR approach continues to study independently a lever (*e.g.* agroforestry) or a set of levers already defined (conservation agriculture, organic agriculture) that do not guarantee the provision of ecosystem services needed in the climate change context. Indeed, the approach by "type of agriculture" should be overcome to focus further on the ecosystem services provision of MBCS (Dardonville et al., 2022) which is the main factor to integrate when designing sustainable cropping systems.

Applied to MBCS focused on climate change adaptation and mitigation ESR framework should be applied to save the scarcer resources under climate change, especially water and irrigation water, and the resources responsible for climate change, especially fuel or nitrogen fertilization and also to limit the impact of extreme meteorological events (heat waves, droughts, late frosts, storms…) by creating a more resilient system. In that objective, "Efficiency" would consist in the optimization of the key resources related to climate change (water, irrigation water, fuel, nitrogen fertilizer) through a better identification of the needs (use of soil humidity sensors, nitrogen monitoring) combined with the use of Decision Support Systems. It can also include the adaptation of the MBCS such as the shift of sowing dates to avoid water or heat stresses. "Substitution" should here focus on the inputs that can help to reduce the use of the key resources *e.g.* in choosing varieties able to cope with heat or water stresses or the partial replacement of mineral nitrogen by green waste compost which will reduce the mineral nitrogen dose and improve soil organic matter which will, in turn, increase the soil water holding capacity. Finally, "Redesign" would use diversification of MBCS through tillage reduction to build a more resilient cropping system in respect with climate change. Redesign is particularly important to limit the impact of extreme meteorological events by introducing the adapted crops and cover crops species and by improving the soil water dynamics such as infiltration and water holding capacity. These rotation and tillage changes will imply to modify the entire management of the MBCS and will also fulfil the objectives of scarce resources and resources responsible for climate change economy.

3. In the implementation: combination of on station, on farm and model studies

After the co-conception of the innovative cropping systems phase, the implementation of the designed cropping systems is necessary. Indeed, while international environmental evaluation (*e.g.* IPCC or IPBES reports) and regional/national monitoring (*e.g.* watershed and rivers

pollutants monitoring) are essential in the agroecological transition framework *to know* to which level the human activities impact the environment, they are not sufficient to identify more local impacts, at the field level. The quantitative assessment and the comparison between MBCS is a way *to understand* what are the set of practices that damage the environment and which processes lead to the results obtained.

Both on-farm and on-station experiments should be used since they are very complementary. The implementation of an innovative cropping system on station will help to better control the environment and a various range of combination of agroecological possibilities can be implemented and compared with a reference cropping system present on the farm. The other advantage is that on station cropping systems can be evaluated on impact performances. Based on quantitative *in situ* measurements, on-station cropping systems approaches should be more deeply used. Along with the cost of such experiments, the major limitation of that experimental cropping system approach is the lack of representativeness of the results obtained. This drawback can be partially limited by the choice of an accurate reference cropping system, representative of average regional practice or normative references (Deytieux et al., 2016). Nevertheless, these experimental cropping systems remain conducted on small surface by people that are not farmers.

To face that problem, it is possible to assess directly the systems implemented by farmers on their farm. This will be much more efficient for the local farmers knowledge and will allow a better appropriation of the results by the farmers. Studying a cropping system on a farm will also foster the integration of the cropping system into the farming system. That approach was developed recently by (Alletto et al., 2022c; Boeraeve et al., 2020) on MBCS. It is promising because the MBCS studied are more mature, representative, and credible at the farm scale while on station approach is difficult to upscale from field. It is a way to integrate farmer's knowledge and skills to the research facilities since the farmers are the pilot of those MBCS. Finally, it has also more chance to promote the relevance of the redesigned MBCS amongst the commercial partners from upstream and downstream and the farmers.

Cropping system experiments in farmers field is particularly interesting if the farmers that manage the MBCS are part of a farmers' network (Slimi et al., 2021). These networks are essential for the spread of innovation throughout the territory. Since the "Grenelle de l'environnement" in 2007, French government, through subsidies and funded support (GIEE, DEPHY-FERME network, "30000 groups" …) enhances the constitution of groups of farms to facilitate the agroecological transition of cropping systems and the related technical dissemination and exchange.

However, on-farm studies should not replace totally on station studies because it is rare that a reference comparison can be tested on the same study site. Moreover, the disruptive innovations that can be tested simultaneously is lower since farmer evolution is supposed to be more incremental, especially in the case of climate change (Zobeidi et al., 2022). It is also more complicated to collect quantitative data on farm. As a consequence, the cost (time and money) of the observations can be prohibitive for research because several sites are needed at the regional scale to be representative – to some extent – of the area studied and evaluation remains mainly limited to a small set of sustainability indicators.

When accurate, the cropping system approach might be completed by an analytical work to bring specific information on techniques poorly studied. For example, the study conducted by

(Alletto et al., 2022a) allowed to identify what was the most adapted cover crop on a specific no tillage MBCS of southwestern France. The limit is that these studies do not consider potential synergies and carryovers between techniques. For the moment, few entire MBCS using ESR approach have been yet tested and published by research (Adeux et al., 2017; Giuliano, 2016; Giuliano et al., 2021).

4. Crop models, a complementary tool to explore scenarios and to facilitate cropping system design

Undoubtedly, models are able to cope with interactions between crops, environment and cropping systems (Jeuffroy et al., 2014). Models can work on several scales, from plants to food webs (Tixier et al., 2013). They are also able to study plots and watershed dynamics (Mottes et al., 2014). The interest of the models relies on their capacity to evaluate the agronomic practices on characteristics (particularly, environmental conditions) or dimensions (particularly, environmental impacts) that cannot be explored experimentally because of the cost, the time needed or a technical impossibility. In that way, they are a complementary tool to experimental studies on MBCS. Models can be used in the beginning of a co-designing process to evaluate *ex ante* if the MBCS designed is susceptible to reach the objectives assigned. Models are also useful after each cropping season or at the end of the experiment to explain some results observed or to increase the genericity of the results in simulating the MBCS in different pedoclimatic contexts.

At the plot scale, crop models such as STICS (Brisson et al., 1998) are able to simulate plant growth under contrasted management (fertilization, irrigation, sowing dates…) and finally evaluate these impacts on the environment. They are thus a tool to study, understand and also design adapted cropping systems (Gaudio et al., 2019). Moreover, the recent consideration of innovative agronomical practices, such as intercropping (Gaudio et al., 2019), allows more flexibility in the practices considered and permits thus to study more innovative cropping systems. However, lack of reference on some innovative management practice can limit the pertinence of the models. Particularly, reduced tillage is often modelled by changes in soil density, organic matter redistribution or porosity changes but does not take into account biological parameters such as microbial biomass changes (Maharjan et al., 2018). Nonetheless, the difference of infiltration capacity evolution between conventional and reduced tillage might also not be considered by models (Alletto et al., 2015). Water dynamics evolution under reduced tillage are also not well represented, which can be impactful for some environmental issues such as pesticide fate or N_2O-emissions (Brilli et al., 2017; Mottes et al., 2014). As a consequence the simulations can generate results with an important variability, according to the simulation choices (Marín-Benito et al., 2018; Mottes et al., 2014).

Models are also useful to understand the influence of a cropping system on soil parameters that change slowly (*e.g.* soil organic carbon such as the model AMG; Clivot et al., 2019) and on soil process that are particularly difficult to measure (*e.g.* soil bulk density). (Poeplau and Don, 2015) were able to evaluate the potential of carbon storage in the soil allowed by cover crops while (Clivot et al., 2019) evaluated the impact of entire cropping systems on the same parameters. However, in both cases, an important variability remained unexplained. Finally, up

to now, soil and crop models are not always associated because of a coupling complexity (Mueller et al., 2010).

Models would be particularly interesting in the case of climate change to evaluate the sensitivity of crops to variable climate conditions (temperature and precipitations) and to identify how the productivity would evolve according to the location (Debaeke et al., 2017; Pullens et al., 2021). The model performance with actual climate are generally good but remain variable (R^2>0.8 for Newman and Furbank, 2021). However, all the authors warn that predictions of crop performance under future climate include an important uncertainty because of the difficulty to predict how exactly the climate will change (*e.g.* rainfall distribution), the unpredictability of the biotic stresses (*e.g.* new diseases) and the impossibility to predict technical problems in the field arising from extreme climatic events (*e.g.* flooding in the field that prevents from sowing). Moreover the influence of some local adaptations techniques (*e.g.* nitrogen fertilization) are difficult to be quantified by crop models (Corbeels et al., 2018).

Ongoing model developments can facilitate their use by research, students and, more generally, by all the stakeholders concerned. Qualitative aggregative models such as IPSIM that helps at managing an injury profile according to the management and environment (Aubertot and Robin, 2013) are more easy to adopt. At the difference with mechanistic models that aim at transcribing the processes that occur in the field, IPSIM uses an aggregation method based on DEXi software. It has also the advantage to be a generic approach that can be adapted to a great range of crops and diseases, pests or weeds. That approach on aggregation method could also be developed for environmental impacts such as the presence of pesticides in drainage water and for multicriteria assessment, especially using fuzzy methods to limit threshold effects (Bockstaller et al., 2017). Finally, models can be included in more easily appropriated forms such as serious games like Interplay that aims at evaluating the supply of ecosystem services permitted by intercrops, according to farmers objectives (Meunier et al., 2022).

III. A multicriteria assessment approach integrating ecosystem services and environmental impacts

1. From co-design to evaluation

The objectives of MBCS and the way it will be evaluated have to be integrated from the very beginning of the design process. Target objectives will indeed influence the choice of crops and related management. To evaluate properly their sustainability, the MBCS objectives must integrate economic, social and environmental impacts that are adapted to the local context (farm, territory).

As these objectives are set, the way their level of achievement will be appreciated needs to be considered. As the need for co-designing often comes from environmental (*e.g.* water quality), social (*e.g.* workload) or economical (*e.g.* income) issues that can be combined, the indicators chosen must be able to depict the evolution of the performances of the cropping system (Lairez et al., 2016). If the initial context and initial problematic needs to be integrated into the set of indicators, it is also important to consider the other main ES of the cropland necessary to fulfil for the territory considered. Indeed, the progress on a specific indicator doesn't necessarily induces a progress on all the indicators.

According to the Driver-Pressure-State-Impact-Response (DPSIR) framework different kind of indicators could be used to evaluate MBCS (Kristensen, 2004; Lairez et al., 2016):

- Pressure indicators that characterize the level of inputs applied to a CS (mineral N, pesticides through the Treatment Frequency Index…) or the level of emissions but do not inform on the impact of input level on the environment (soil, water, atmosphere, biodiversity)
- State or Impact indicators that refer to the state of the environmental compartments and agroecosystem such as concentration of pesticides in drainage water, amount of N_2O denitrified in the atmosphere, microbial biomass in the soil… They are more precise than pressure indicators since they include the sensitivity of the environment in the evaluation. Economic and social indicators can also be included in that category.

Complementary to the DPSIR framework, ecosystem services can also be quantified using dedicated indicators. The concept of ecosystem services evaluation of a cropland is particularly interesting and was developed several years ago (Foley et al., 2005). It relies on a conceptual framework that includes eight ecosystem services that had to be provided by agroecosystems: crop production, forest production, habitats and biodiversity preservation, water flow regulation, water quality regulation, carbon sequestration, regional climate and air quality regulation and infectious disease mediation. These ES are determined by biophysical determinants (Therond et al., 2017b) that are also interesting to measure in order to understand the potential of ES delivery of a given agroecosystem.

However, some publications effectively evaluate ES and their determinants (Boeraeve et al., 2020; Garbach et al., 2017; Schipanski et al., 2014; Syswerda and Robertson, 2014) but this has not been yet developed for MBCS. In most of the studies, the quantification of ES aims at

comparing different type of practices but fails at measuring the level of ES provided without external inputs (mainly mineral N, pesticides). For example, concerning weed regulation, the studies indicate the level of regulation provided by the system but do not allow to measure the influence of weeding on weed flora. This could be done in integrating unweeded areas that allow to quantify the regulation potential of different cropping systems, as it was made by Adeux et al. (2019) for a slightly different objective. (Soulé, 2022) also produced an useful contribution by studying correlations between several ES and their environmental impacts. They revealed that the correlation between ES and environmental impacts is very variable according to the ES considered. The correlation was high between ES "soil protection erosion" and erosion impact but low between nitrogen supply ES and use of mineral nitrogen, a pressure indicator. The quantification of ES "N provided by agroecosystem" without the N inputs was also done by Therond et al. (2017b) at a national scale. This effort must go on and be adapted to MBCS at field scale to fully operationalize ES evaluation in MBCS.

Nevertheless, the operationalization of ES quantification at the cropping system level and ES adaptation to local context remain a challenge for research.

2. Quantification of ecosystem services

Ecosystem services can be quantified biophysically and economically (Therond et al., 2017b). The framework of strong sustainability supports that economic activities preserve the environment and improve social wellbeing (Oliveira Neto et al., 2018), when weak sustainability assumes a substitutability between economic, social and environmental capitals. From an agronomical point of view, the strong sustainability framework thus recommends to evaluate ES from a biophysical point of view rather than from an economical point of view since the good functioning of agroecosystems is based on biophysical processes.

Different approaches can be used to evaluate ecosystem services of a cropping system according to the type of ecosystem service considered. In all cases, data acquisition in the field is necessary to inform directly on some ES (*e.g.* soil organic carbon measure to evaluate the ES of soil carbon storage) or to have sufficient data for the parametrization of the models used to evaluate ES (*e.g.* measurement of mineral N in the soil at maize sowing and N in the plant at harvest to evaluate the ES supply of mineral N to crops), as it was done by (Soulé, 2022). That requires the data on crop practices as well as soil characteristics. An alternative to model uses, that can be poorly adapted to some situations such as reduced tillage as they have been developed for conventional tillage practices, is to carry out laboratory experiments, that could be useful for some ES such as the natural pesticide mitigation by soils or GHG-emissions by soil (Cassigneul et al., 2016; Syswerda and Robertson, 2014).

It is also possible to introduce within the field specific check treatments to measure some specific ES: Adeux et al. (2019) implemented small unweeded areas that could be used to measure the ES "weed regulation" provided by a given cropping system. The inclusion of a check plot management with no fertilizer nor pesticides into a cropping system is a very interesting way to disentangle the part of an ES due to the cropping system management and the part attributed to the use of external inputs. That quantification is an important research question to focus on during next years (Therond et al., 2017b).

Another complementary approach for the evaluation of ES is to focus on the measure of ecosystem functions or determinants of the ES of interest. For example, quantification and identification of pollinators is a way to evaluate the pollination ES (Toivonen et al., 2022), aphid counting can be used as a proxy to characterize the pest control ES (Boeraeve et al., 2020).

Quantification of some pressure indicators such as the use of pesticides can also be seen as an indirect measurement of an ecosystem dis-service, meaning that the agroecosystem has a bad functioning (Soulé, 2022).

Finally, it is possible to estimate some ES through literature review and expertise (Schipanski et al., 2014). That method should nevertheless be used very cautiously for agroecological MBCS since these systems have been yet poorly studied and thus, literature availability will be limited, in particular for a specific pedoclimatic context.

3. Impacts quantification of MBCS

Complementary with ES evaluation, environmental state or impact quantification is important to inform on the effect produced at the plot level by the cropping practices on the environment and on social and economic aspects. While pressure indicators are based on technical field operations and thus relatively easy to collect, they only provide information on the level of input use. Impact indicators can indicate state change of the environment as a result of that level of input and agroecosystem functioning.

The indicators chosen for the evaluation must represent the main stakes of MBCS on the different compartments of the environment (Figure V.3). Ideally, they should be set up by all the stakeholders of the territory (farmers, suppliers, transformers, consumers and citizens). As soil is the environment compartment the most linked with the cropping system, several state indicators can be monitored concerning the biological (*e.g.* microbial biomass amount), chemical (*e.g.* P content) or physical (*e.g.* aggregate stability, erosion losses (Seitz et al., 2019)) fertility. Soil organic carbon is also an important indicator to survey as it plays a major role for these different types of fertility, for several ES and is also essential to characterize GHG emissions and energy use of CS (Hercher-Pasteur et al., 2020; Therond et al., 2017b). All these soils indicators are routine measures made in laboratory thus relatively easy and inexpensive.

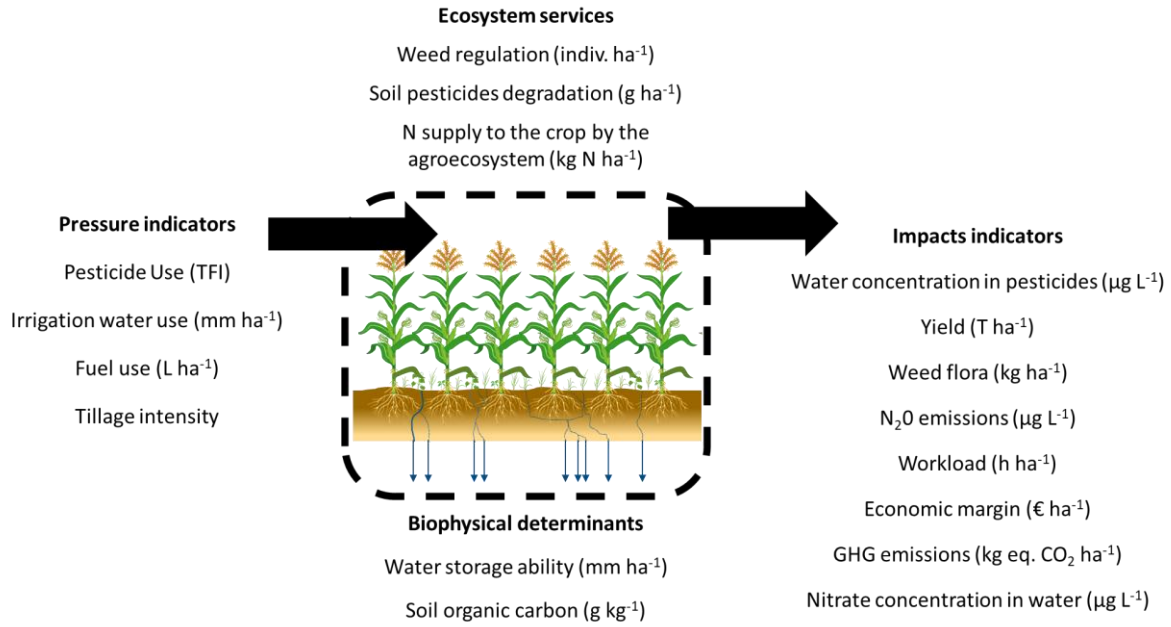


Figure V.3: Examples of indicators, ecosystem services and biophysical determinants that can be measured on a MBCS

Atmosphere impacts can also be measured *in situ* through specific devices such as automatic chambers that can follow the N_2O emissions throughout the crop cycle (Peyrard et al., 2016). Pesticide volatilization can be measured through wind tunnels (Bedos et al., 2017) but that monitoring cannot last throughout the crop cycle and remains limited to the post-application phase. Impacts of cropping systems on water quality can also be measured through indicators calculated from data collected thanks to plate lysimeter systems that allow to monitor pesticide and nitrate concentrations in drainage water (Giuliano et al., 2021).

Finally, quantitative impacts on biodiversity can be measured. When focusing at the field scale, only biodiversity with low mobility can be accurately evaluated, which is globally the case of soil biodiversity: microorganisms and macrofauna. Weed diversity can also be evaluated at field scale, which can be particularly relevant for the conservation of biodiversity and the contribution of weeds to support pollinators feeding for instance (Balfour and Ratnieks, 2022). During the interpretation of the data, it is important to keep in mind that all the possible weeds – and to some extent, soil biodiversity – cannot be present in a given field because of dispersal and environmental constraints (Fried et al., 2016).

Methodological developments are particularly important actually to determinate soil state and ecological functions using enzymatic activities (Nivelle et al., 2016) or pedotransfer functions (Vogel et al., 2019) to estimate essential soil functions such as nutrient cycling, carbon storage or water storage through the use of soil texture or soil bulk density measures.

Direct field measures of impacts allow to inform on the state of the ecosystem in the very particular context of the cropping system. However, they are cost and time consuming. Thus, to valorise the data collected in a particular place, models can use that data as reference for some processes and then extrapolate the results to other contexts. Moreover, models allow to complete the impacts characterization on important stakes particularly difficult to measure while well modelled as GHG-emissions with models such as the Farm Energy Analysis Tool (Camargo et al., 2013) or AMG to evaluate soil carbon evolution (Soulé, 2022).

For the impacts that cannot be evaluated at the plot level (pollinators presence, filling level of the watershed…), indicators at higher scales can be measured at the landscape or watershed level. However, if that indicator is well informed, it could be possible to quantify the contribution of a given CS to a more global impact.

Economic impacts also need to be characterized during the evaluation (Soulé, 2022). Data collected at field level can be extrapolated to the farm scale if all the technical operations (*e.g.* tractor and tools used, tool width, speed of work, machinery and supply costs) have been informed. Based on the same data acquisition, the only relevant "social" aspects that can be quantified at the plot level is the workload (Soulé, 2022).

4. Interpretation of evaluation results

Two elements seem particularly interesting to be looked at when interpreting evaluation results obtained: the choice of reference values and the aggregation of results.

Once multicriteria assessment of an agroecological MBCS is done, interpretation of the results needs to gather external reference values (Deytieux et al., 2016; Lairez et al., 2016). They can be of different nature. Absolute threshold could be used for indicators according to toxicity norms for water (*e.g.* nitrate European drinkability norm of 50 mg $N\text{-}NO_3^-$ L^{-1}) or grain quality (e.g. mycotoxin deoxynivalenol norm of 1000 µg kg^{-1}) that derive from scientific and policy data. Other absolute values can be used as they represent an ecological threshold that must be maintained to have an agroecosystem that functions "well". This is the case for the soil carbon shift that has to be positive. At higher scales, it is the principle that underlies the planet boundaries necessary to respect to maintain Earth integrity (Persson et al., 2022).

However, relative values are more commonly used (Soulé, 2022). Despite they cannot answer to the "absolute" sustainability of a given CS, they facilitate the comparison between options (here, CS) and the characterization of evolution. The relative reference used to interpret the results can be "spatial references". These references can be a "reference system" that is representative of the average practices in the region considered – that might not always be easy to define – or a local CS implemented in parallel with the tested CS (Deytieux et al., 2016). The other kind of relative reference is "historical" that corresponds to the ancient CS conducted on the farm/experiment. A limit of that choice of reference is the evolution of the context that might limit the relevancy of the reference in the medium term (policy changes such as pesticides withdrawal, price variability…). As for the objective of the MBCS, the choice of the reference values might be made early in the co-design process.

Cropping system approach, by testing combination of practices, is able to benefit from and quantify trade-offs between techniques. However, results from multicriteria assessment might be difficult to interpretate or to compare for policy makers. Despite access to basis indicators is necessary for specialist interpretation, aggregation of results from multicriteria assessment might be necessary to discriminate several options and improve results dissemination, even if aggregation is often criticized for its bias, lack of transparency and/or reliability (Bockstaller et al., 2017; Chopin et al., 2021). Different methods exist (composite indicators, outranking methods and mixed methods based on decision trees). However, the aggregative methods based on quantitative and qualitative data might be the most promising for CS comparisons (Bockstaller et al., 2017).

5. For long term experiments: taking into account the temporal variability through the resilience analysis

There are plenty of elements that can influence MBCS performances and they just seem to reinforce years after years. During next years, MBCS will have to deal with climate change that can lead to heat waves, droughts or flood stresses, price (inputs and grains), limited resources availability (irrigation water, phosphorus fertilizers…). It is thus important to analyse how MBCS cope with these trends and hazards, which is the objective of the resilience analysis (Peterson et al., 2018). Resilience is based on four criteria that are the level of performance, its stability, its resistance and its recovery (Figure V.4).

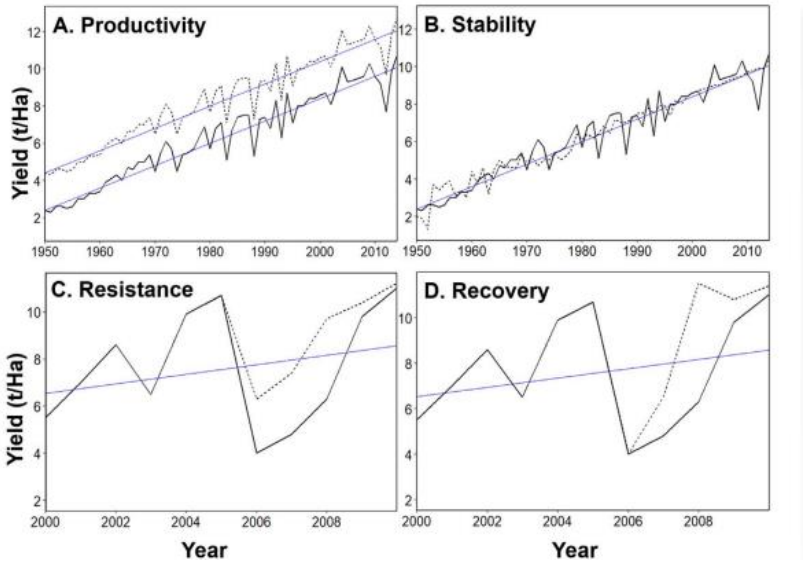


Figure V.4: Description of the four components of resilience, extracted from (Peterson et al., 2018)

Long term trials are for the moment mostly studied through their level of performance, analysed by research through the mean calculation. However, other metrics can be used to define the performance level such as the intercept of linear or mixed regressions (Dardonville, 2021). The CS studies often complete their evaluation on a given criteria with a characterization of its standard deviation that is a way to evaluate stability performances across space (multiple locations) and/or time (multiple years). Stability can also be studied through residuals of linear/mixed models regressions (Dardonville, 2021). From a research point of view, it would be a great methodological progress for long term trials to study also resistance and recovery that are both parameters highly affected by disturbances (Peterson et al., 2018). Years would not only be as replicates of the same experiment but as set of disturbances to which the MBCS is exposed.

Recovery is the ability of a system to go back to baseline functionality after a disturbance and is equivalent to "engineering resilience" (Peterson et al., 2018). It can be particularly interesting to characterize hysteresis that is to say a quick degradation that needs a longer time to recover, which can be the case of soil structure degradation after an erosion event. From an economical point of view, recovery was characterized by Sneessens et al. (2019) as "the number of years to

recover from a disruption of -25%" for a given indicator. This definition of recovery could be adapted to biophysical indicators.

Resistance is the ability of a system to maintain its performance while it faces a disturbance. It can be calculated by the frequency when an indicator value decreases more than 25% in respect with the baseline level. It can also be calculated as the probability to have low level (<75%) of performances (Dardonville, 2021).

It is important to follow the indicators on a long period to measure the performance evolution. An alternative to test resilience of cropping systems is to simulate disturbances with models by disturbances simulations (*e.g.* a reduction in precipitations, variation of input prices…). Nevertheless, for the moment, most of the scientific CS studies only consider the years as replicates, without studying the dynamics that is interesting *per se*. When the dynamics of performances is evaluated, it is overwhelmingly done using only one indicator of performance, yield in most of the cases (Dardonville, 2021). Due to the recent development of research methodologies, it is however an attainable research objective for next years, to realize dynamical multicriteria assessment of impacts and ecosystem services (Chopin et al., 2021) to evaluate resilience and sustainability of cropping systems.

IV. Perspectives de recherche pour les expérimentations longue durée de Lamothe

Les fronts de recherche discutés dans ce chapitre V ouvrent des perspectives intéressantes pour valoriser les données produites sur l'expérimentation systèmes de culture de Lamothe et diffuser ainsi de nouveaux résultats dans la communauté scientifique et technique.

1. Evaluation dynamique des performances

Concernant l'évaluation dynamique des performances, de premières analyses ont été réalisées sur le rendement sur la période après la « phase de transition » des systèmes de culture, soit la période 2014-2022 (figure V.5). Alors que les moyennes entre MM_{LI} et MM_{CTOM} sont proches, les dynamiques de performances sont différentes avec un impact beaucoup plus fort sur le rendement de l'année 7 (2020) sur MM_{LI} mais un retour de bonnes performances en 2021 et 2022, à la différence de MM_{CTOM} dont la dynamique semble être négative. Cette évaluation, actuellement menée sur le rendement, pourra être réalisée pour l'ensemble des indicateurs mesurés ou calculés sur le dispositif. Après agrégation des résultats de l'évaluation multicritère, il sera ainsi possible d'évaluer la dynamique de durabilité des différents systèmes de culture mis en œuvre. Cette étude dynamique permettra de mesurer la résilience des systèmes par rapport à différents événements climatiques des dernières années (printemps pluvieux en 2018, difficultés de gestion liées au Covid-19 en 2020, sécheresse estivale 2022…). L'étude de la dynamique des performances pourra être modélisée via l'utilisation de modèles linéaires généralisés, plus performants pour décrire les dynamiques interannuelles que les modèles linéaires utilisés dans le chapitre IV.

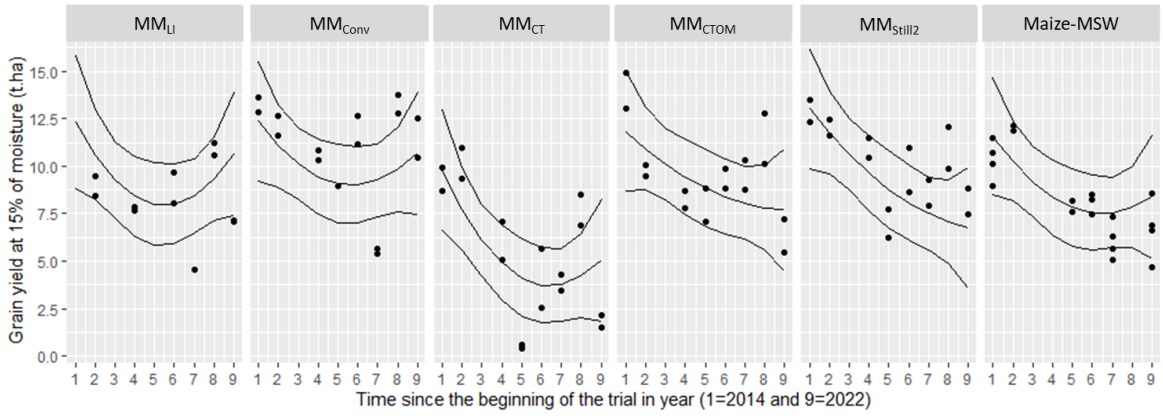


Figure V.5 : Evolution du rendement au cours du temps pour six systèmes de culture mis en œuvre sur l'expérimentation longue durée de Lamothe (Deremetz, 2023, communication personnelle)

Toujours du point de vue de l'évaluation des performances, un front de recherche important sur l'expérimentation longue durée de Lamothe est également l'analyse et l'évaluation multicritère des rotations dans leur ensemble. En effet, pour le moment, seul le maïs de la rotation courte a été analysé et publié (chapitres II, III et IV). Le fait que la rotation « Alimentation Humaine » aura fait deux cycles complets en 2024 permettra de comparer deux systèmes de culture en

rotation et facilitera ainsi la communication des résultats. Une certaine agrégation des indicateurs permettra sans doute de faciliter la comparaison des résultats entre les systèmes en monoculture et ceux en rotation, qui incluent d'autres cultures (blé tendre, soja, avoine…).

2. Compréhension des processus

Les suivis réalisés sur les systèmes de culture mis en œuvre depuis l'automne 2010 permettent de faire une analyse fine des services écosystémiques liés à l'azote : production d'azote minéral disponible pour les cultures et valorisation de l'azote par les systèmes. En effet, les reliquats d'azote en début et fin de culture et en sortie d'hiver ont été quasi-systématiquement mesurés chaque année sur l'ensemble des parcelles, tout comme les teneurs en azote des récoltes et des résidus de culture. La teneur en azote minéral a également été mesurée dans un certain nombre de lixiviats. A partir de ces données d'entrée, il sera possible de réaliser des modélisations via des outils de croissance des cultures (*e.g.* STICS) afin de faire des bilans complets de l'utilisation de l'azote dans les différents systèmes, de simuler les impacts sur la qualité de l'eau et l'environnement et de mesurer les services écosystémiques liés au cycle de l'azote.

Un autre front de recherche concerne l'impact de la communauté adventices sur le rendement. En effet, le processus de différentiation des communautés adventices entre les systèmes de culture identifié dans le chapitre III a continué, avec de nouvelles espèces qui sont devenues plus dominantes sur certaines parcelles (e.g. *Setaria glauca* sur MM_{CT} et MM_{CTOM}). Les communautés sont très contrastées entre les systèmes de culture et leurs impacts sur la flore sont variés : des biomasses adventices identiques entre deux systèmes de culture peuvent mener à des rendements très contrastés. Ainsi, des analyses de relation entre biomasse adventice et rendement vont être réalisées et accompagnées d'une analyse des communautés adventices et de leur évolution. Les premiers résultats de ces analyses seront communiqués lors du 25ème COLUMA (journées internationales sur la lutte contre les mauvaises herbes) en décembre 2023. Pour affiner la compréhension des relations entre adventices et rendement dans les systèmes de culture maïsicoles, il est par ailleurs envisagé de remettre en place des zones 0 adventice au sein des parcelles.

Afin de compléter la connaissance des communautés adventices sur les différents systèmes de culture, des mesures de stock semencier sont en cours de réalisation (prélèvements réalisés en mars 2023) en partenariat avec l'UMR Agroécologie. Ces mesures permettront notamment de mesurer plus finement l'impact des différentes stratégies de gestion de la flore adventice mises en place sur les différents systèmes de culture (Mahé *et al.*, 2021).

3. Indicateurs d'état et de performance

Au fur et à mesure des développements méthodologiques et des questionnements scientifiques, de nouvelles possibilités de suivi s'ouvrent pour le dispositif expérimental. Ainsi, jusqu'à présent l'ensemble des paramètres liés à la vie du sol ont été peu suivis, alors même que la vie du sol est au cœur de multiples processus et services écosystémiques (Therond *et al.*, 2017b ; cycle de l'azote, dégradation des pesticides, séquestration de carbone…).

Afin de mieux comprendre les différences de niveau de vie du sol entre les systèmes de culture, de premières mesures de biomasse microbienne ont été réalisées en 2019 et ont été complétées à l'automne 2021 par des mesures d'activité enzymatique des micro-organismes du sol qui

permettront d'évaluer le fonctionnement du sol pour différents processus (minéralisation de l'azote, séquestration du carbone…) et la production des services écosystémiques liés (Nivelle *et al.*, 2016).

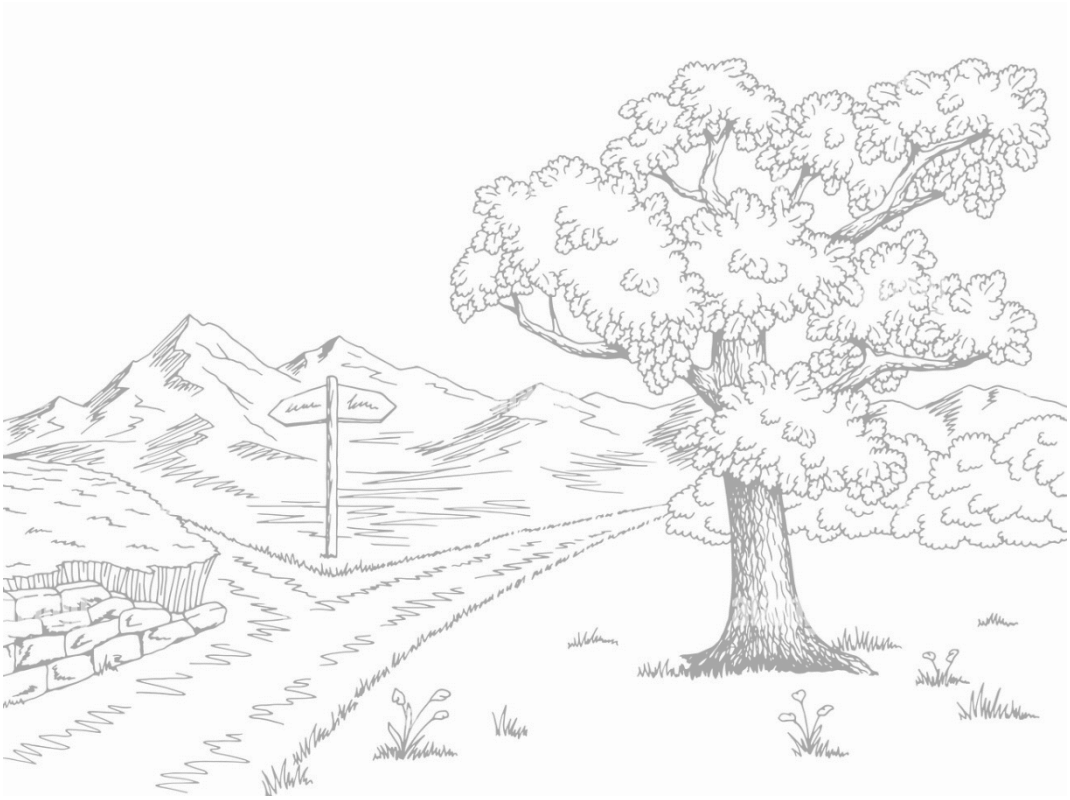
Ces suivis de la vie du sol ainsi que ceux liés au stock semencier pourront être réalisés à pas de temps régulier afin de mesurer l'évolution de ces paramètres dans le temps et évaluer l'impact de certains choix de gestion ou de conditions pédoclimatiques.

4. Prise en compte des dimensions territoriales et mise au point et évaluation d'un système de culture en agriculture de conservation des sols

Dans le cadre du programme de recherche ALIAGE « s'Appuyer sur Les Innovations couplées d'AGriculteurs pour soutenir l'Émergence de systèmes agricoles sans glyphosate », un système de culture s'appuyant sur les trois piliers mobilisés en agriculture de conservation des sols (travail minimal du sol, couverture permanente, diversification de la rotation) a été intégré au dispositif expérimental en 2023. Ce système de culture vient compléter la diversité des pratiques mises en œuvre.

Ce projet ALIAGE s'appuie sur la démarche d'innovations couplées qui consiste en une innovation conjointe portant à la fois sur le système de culture (système technique), sur l'organisation collective et sur le machinisme (Boulestreau *et al.*, 2022). Au-travers de la dimension « organisation collective », ce projet est l'opportunité d'améliorer les interactions avec les acteurs du territoire intéressés par les expérimentations menées (chambres d'agriculture, coopératives et structures de conseil, agricultrices et agriculteurs, instituts techniques, recherche…). Ces acteurs ont été impliqués dès le démarrage du système de culture via un atelier de co-conception qui a réuni une vingtaine d'acteurs du territoire. D'autres ateliers et visites, permettant de partager les premiers résultats et recueillir les avis des acteurs locaux en vue de prendre des décisions stratégiques sur l'expérimentation, sont prévus dans les mois et années à venir afin de permettre une meilleure appropriation du dispositif expérimental au sein du territoire.

Conclusion



Le changement climatique devient tous les jours un peu plus prégnant, comme en témoigne la chute de la production maïsicole française suite à la sécheresse et aux chaleurs estivales en 2022 (-22.3 % de production par rapport à la moyenne 2017-2021 ; Agreste, 2023). La prise de conscience par la société des impacts possibles de ce changement climatique vient exacerber les controverses liées à l'usage des ressources en agriculture comme en témoigne le conflit, ravivé par la sécheresse hivernale, autour du partage et de l'usage de l'eau à Sainte-Soline. La question des impacts de la production de maïs sur l'environnement et la qualité de l'eau est également omniprésente, notamment avec la question du possible retrait du S-metolachlore, un herbicide majeur utilisé en maïs. Face à ces enjeux majeurs, les acteurs du monde agricole - et au-delà - n'adoptent pas de position commune ni coordonnée, ce qui pourrait tendre à accroître l'écoanxiété et les tensions. Pour la recherche, cela vient renforcer l'importance de se saisir des questions de recherche posées.

Le maïs, plante emblématique du paysage agricole français (2.6 millions d'ha en 2022 ; Agreste, 2023), se situe au cœur de ces enjeux liés au changement climatique, à la gestion de l'eau et à l'évolution de la réglementation. Cette culture cristallise les tensions entre monde agricole et société civile, souvent citée comme exemple relativement au fort usage de l'eau d'irrigation en période estivale ou encore pour l'importance de ses surfaces de culture à destination de l'alimentation animale. La revue bibliographique réalisée lors du chapitre I montre que les problématiques environnementales soulevées en France sont similaires à celles présentes dans les principaux bassins de production mondiaux du maïs (Etats-Unis, Chine et Europe). Ces limites environnementales encouragent à développer les futures recherches sur les systèmes maïsicoles dans le cadre de la durabilité forte, reposant la non-substituabilité entre capital naturel, volet économique et volet social (chapitre V). Toutefois, le maïs possède d'indéniables avantages physiologiques en faveur d'un bon fonctionnement de l'agroécosystème, en termes de production de biomasse, levier important d'atténuation du changement climatique, de maîtrise technique et de rentabilité économique pour les exploitations (chapitres I et V).

Au regard de la veille bibliographique menée, deux questions doivent ainsi être traitées par la recherche et la société concernant le maïs :

- Au regard de ses impacts environnementaux et de sa destination, quelle place pour cette culture dans les systèmes alimentaires à l'avenir ?
- Comment les pratiques agroécologiques peuvent-elles i) améliorer les services écosystémiques produits dans les agroécosystèmes produisant du maïs et ii) réduire les impacts environnementaux de la production de maïs ?

La réponse à la première question impose une nécessaire étude des systèmes alimentaires dans lesquels s'insèrent le maïs et les produits animaux issus de sa consommation au travers d'une approche pluridisciplinaire, et ne doit pas être éludée au moment d'interpréter les résultats issus de cette thèse. Les publications scientifiques issues de ce travail de thèse contribuent à apporter des éléments de réponse à la deuxième question posée et à éclairer les débats actuels, afin notamment d'accompagner les politiques publiques en faveur des systèmes de culture les plus prometteurs. Les principaux résultats scientifiques des travaux expérimentaux longue durée menés montrent que :

- Une démarche systémique de co-conception de systèmes de culture mobilisant le cadre Efficience-Substitution-Reconception en vue d'atteindre des objectifs

environnementaux, économiques et sociaux produit des résultats valides agronomiquement et valorisables scientifiquement, notamment du point de vue de l'étude des interactions entre pratiques (chapitres II, III, IV). Ceux-ci peuvent être étendus à d'autres situations pédoclimatiques notamment via la modélisation (chapitre V)

- La démarche d'évaluation multicritère mise en œuvre permet de clarifier les éventuels compromis qui peuvent être faits entre différentes performances (chapitre II)
- L'évaluation environnementale *in situ* des impacts permet une évaluation plus précise des performances environnementales et permet de mieux comprendre le lien entre niveaux de pression et impact environnemental (chapitre IV)
- La combinaison de certaines pratiques (introduction de cultures intermédiaires, désherbage mécanique, variétés plus précoces, désherbage localisé sur le rang, pilotage de l'irrigation et de l'azote minéral…) au sein de systèmes de culture a permis de réduire de 15 à 50% les différents impacts environnementaux de la monoculture de maïs conventionnelle (réduction des émissions de gaz à effet de serre, de l'utilisation de l'eau d'irrigation et des intrants azotés, amélioration de la qualité de l'eau) tout en maintenant ou améliorant les performances économiques et sociales obtenues avec la monoculture de maïs irriguée de référence (chapitres II, III, IV)
- L'évaluation des performances pendant la phase de transition (chapitre II) et sur le temps long (chapitres III et IV) sont nécessaires, en particulier dans le cas de systèmes de culture innovants, encore méconnus et dont les performances continuent à évoluer au cours du temps, même après plus de dix années de mise en œuvre (chapitre V)

Au regard de cette dynamique temporelle, il apparaît nécessaire de poursuivre les efforts engagés sur l'évaluation multicritère de la durabilité des systèmes de culture en maintenant ces expérimentations systèmes de culture. Menées sur le temps long, ces expérimentations permettent de mesurer la dynamique des performances des systèmes de culture au cours du temps et d'évaluer leur résilience face aux aléas climatique via leur niveau de performance, leur stabilité et leurs capacités de récupération et de résistance. L'évaluation de la résilience apparaît ainsi comme un front de recherche important. Toujours concernant l'évaluation multicritère des expérimentations systèmes de culture, la démarche d'évaluation doit également évoluer dans le choix d'indicateurs permettant de s'approcher au maximum de la mesure d'impacts environnementaux, des services écosystémiques majeurs attendus et/ou de leurs déterminants biophysiques. Il convient néanmoins de s'attacher au fait que ces indicateurs soient réalisables, pertinents et compréhensibles.

Bien que ces expérimentations soient importantes pour faire progresser la connaissance sur les systèmes de culture maïsicoles agroécologiques, celles-ci doivent être menées conjointement avec d'autres approches : i) expérimentations analytiques (en parallèle ou imbriquées dans les expérimentations systèmes de culture) afin de répondre à des questions plus précises telles que l'évaluation de l'impact des adventices sur le rendement, ii) modélisation afin de mieux comprendre certains processus tels que la dynamique de l'azote et/ou d'extrapoler les résultats obtenus à d'autres contextes pédoclimatiques, notamment afin d'anticiper les problématiques à venir. iii) Il convient aussi de travailler sur l'échelle plus large de l'exploitation agricole et du territoire, notamment via des réseaux d'agriculteurs.

Ces échelles exploitations et territoires doivent en effet être inclues tout au long du processus de co-conception, de mise en place et d'évaluation des systèmes. En effet, la participation de

l'ensemble des acteurs locaux (producteurs, acheteurs, transformateurs, citoyens…) permettra d'améliorer la pertinence des systèmes de culture mis en œuvre, le partage des résultats, leur articulation avec les autres systèmes de production dans les exploitations agricoles et facilitera leur diffusion dans les territoires. La territorialisation des approches de co-conception et de co-évaluation apparaît là-aussi comme un front de recherche important.

Le nécessaire horizon agroécologique de la production de maïs devra intégrer les leviers agronomiques identifiés, mis en œuvre et évalués dans le cadre de cette thèse (réduction du travail du sol, intégration de cultures intermédiaires, diversification de la rotation, désherbage mécanique, localisation et pilotage des apports d'intrants, choix variétal…) afin d'en réduire les impacts environnementaux. En plus de l'atténuation et de l'adaptation au changement climatique, la mise en action de ces différents leviers devra être adaptée aux enjeux environnementaux locaux, discutés, partagés et développés avec les acteurs du territoire. Le résultat de ces adaptations permettrait d'aboutir au développement d'une diversité de systèmes de culture à l'échelle régionale, dont le niveau d'intensité des pratiques et la mobilisation de leviers agronomiques varient en fonction des enjeux identifiés. Afin de mesurer l'atteinte des objectifs fixés initialement, l'évaluation multicritère dynamique des performances des systèmes de culture doit être la boussole guidant les systèmes de culture maïsicoles vers la transition agroécologique.

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Annexes

I. Matériel supplémentaire – chapitre II - Evaluation multicritère de systèmes de culture agroécologiques alternatifs à la monoculture de maïs

Matériel supplémentaire n°1

		Soil preparation			Maize sowing							
Year	**System**	**Tillage - date**	**Tillage depth (cm)**	**Seed bed preparation - dates**	**Sowing date**	**Variety - Earliness**	**Row distance (cm)**	**Targeted sowing density (plants ha-1)**	**Sowing Machine**	**Sowing depth (cm)**	**Harvest date**	**Residues management type**
2011	**MM_{Conv}**	Moldboard ploughing - March 15th	25	Rottary harrow - March 25th & April 18th Cultipacker - April 18th	April 18th	Maggi - Late	80	90 000	Monosem PNU	3,5	October 14th	Chopped at harvest Disking (October 18th)
	MM_{LI}	Moldboard ploughing - March 15th	25	Rottary harrow - March 25th & April 18th Cultipacker - April 18th	April 18th	Shexxpir - Half-early	80	105 000	Monosem PNU	3,5	October 7th	Chopped at harvest
	MM_{CT}	Strip-till - March 23rd	20	-	April 14th	Shexxpir - Half-early	80	105 000	Monosem PNU	3,5	October 7th	Chopped at harvest Disking (October 10th)
	Maize-MSW	Moldboard ploughing - March 15th	25	Rottary harrow - March 25th & April 18th Cultipacker - April 18th	April 18th	Shexxpir - Half-early	80	105 000	Monosem PNU	2,5	October 7th	Chopped at harvest Disking (October 10th)
2012	**MM_{Conv}**	Moldboard ploughing - March 1st	25	Field cultivator - March 16th Rottary harrow - March 30th	April 6th	Maggi - Late	80	85 000	Monosem PNU	3,5	October 8th	Chopped at harvest Disking (October 9th)
	MM_{LI}	Moldboard ploughing - March 1st	25	Field cultivator - March 16th Rottary harrow - March 30th	April 6th	Shexxpir - Half-early	80	95 000	Monosem PNU	3,5	September 21st	Chopped at harvest
	MM_{CT}	Strip-till - April 5th	15	-	April 5th	Shexxpir - Half-early	80	95 000	Monosem PNU	3,5	September 21st	Chopped at harvest Disking (September 27th)
	Maize-MSW	Moldboard ploughing - January 19th	25	Rotary harrow - April 5th	April 6th	Shexxpir - Half-early	80	95 000	Monosem PNU	2,5	September 21st	Chopped at harvest Disking (September 27th)
2013	**MM_{Conv}**	Moldboard ploughing - April 18th	25	Field cultivator - April 22nd Rottary harrow - April 22nd & April 23rd	April 23rd	Maggi - Late	80	93 000	Kuhn Maxima	4	October 9th	Chopped at harvest Disking (October 18th)
	MM_{LI}	Field cultivator - April 22nd	10	Rottary harrow - April 22nd	April 24th	Shexxpir - Half-early	80	98 000	Kuhn Maxima	4	October 9th	Chopped at harvest
	MM_{CT}	No-till	0	-	May 6th	Shexxpir - Half-early	80	98 000	Kuhn Maxima	4	October 9th	Chopped at harvest Disking (October 18th)
	Maize-MSW	Moldboard ploughing - November 6th	25	Field cultivator - April 22nd Rottary harrow - April 22nd & April 23rd	April 24th	Shexxpir - Half-early	80	98 000	Kuhn Maxima	3,5	October 9th	Chopped at harvest Disking (October 18th)

		Fertilization application					Pesticide applications						
Year	System	Dates	Mode	Type of fertilizer (%N-%P-%K)	Fertilizer doses (kg ha-1)	Total Nitrogen fertilization (kg ha-1)	Dates	Type of product	Mode	Surface treated (%)	Active molecules composition (concentration)	Dose applied per active molecule per hectare (g)	Value of the operation (HTFI)
2011	MM_{Conv}	May 5th	Broadcast applications	17-17-17	412	160	April 18th	Insecticide	Seed coating	-	Thiametoxam (3.5 g cL-1)	57	0
		May 26th		27-0-0	333		May 5th	Herbicide	Sprayer	100	S-Metolachlore (960 g L-1)	1340	0.65
							May 5th	Molluscicide	Mixed with fertilizer	100	Metaldehyde (50 g kg-1)	75	0
	MM_{LI}	May 5th	Broadcast applications	17-17-17	353	130	April 18th	Insecticide	Seed coating	-	Thiametoxam (3.5 g cL-1)	66	0
		May 26th		27-0-0	260								
	MM_{CT}	May 5th	Broadcast applications	17-17-17	412	140	April 5th	Herbicide	Sprayer	100	Glyphosate (360 g L-1)	1800	1
		May 26th		27-0-0	260		April 18th	Insecticide	Seed coating	-	Thiametoxam (3.5 g cL-1)	66.2	0
							May 5th	Herbicide	Sprayer	100	Nicosulfuron (40 g L-1)	55	0.96
	Maize-MSW	May 5th	Broadcast applications	17-17-17	353	130	April 18th	Insecticide	Seed coating	-	Thiametoxam (3.5 g cL-1)	66	0
		May 26th		27-0-0	260								
2012	MM_{Conv}	April 17th	Broadcast applications	33.5-0-0	198	176	April 6th	Insecticide	Seed coating	-	Thiametoxam (3.5 g cL-1)	54	0
		April 17th		0-45-0	440		April 17th	Molluscicide	Mixed with fertilizer	100	Metaldehyde (50 g kg-1)	150	0
		May 31st		46-0-0	240		May 3rd	Herbicide	Sprayer	100	Mesotrione (40 g L-1) + S-Metolachlore (400 g L-1)	150 + 1500	1
							June 1st	Herbicide	Sprayer	100	Nicosulfuron (40 g L-1) + Mesotrione (100 g L-1)	50 + 150	1.83
	MM_{LI}	April 17th	Broadcast applications	33.5-0-0	134	155	April 6th	Insecticide	Seed coating	-	Thiametoxam (3.5 g cL-1)	60	0
		April 17th		0-45-0	440		May 9th	Molluscicide	Distributor	100	Metaldehyde (50 g kg-1)	200	0
		May 31st		46-0-0	240		May 16th	Herbicide	Sprayer	100	Mesotrione (100 g L-1)	150	1
							June 11th	Herbicide	Localized sprayer on row crop cultivator	25	Nicosulfuron (40 g L-1) + Mesotrione (100 g L-1)	15+38	0.50
	MM_{CT}	April 17th	Broadcast applications	33.5-0-0	134	205	March 15th	Herbicide	Sprayer	100	Glyphosate (360 g L-1)	720	0.4
		April 18th		0-45-0	440		April 5th	Insecticide	Seed coating	-	Thiametoxam (3.5 g cL-1)	60	0
		May 31st		46-0-0	240		April 23rd	Herbicide	Sprayer localized on high weed pressure zones	40	Glyphosate (360 g L-1)	288	0.18
		June 27th		27-0-0	185		May 3rd	Herbicide	Sprayer	100	Mesotrione (40 g L-1) + S-Metolachlore (400 g L-1)	150 + 1500	1
							May 9th	Molluscicide	Distributor	100	Metaldehyde (50 g kg-1)	200	0
							June 1st	Herbicide	Sprayer	100	Nicosulfuron (40 g L-1) + Mesotrione (100 g L-1)	50 + 150	1.83
	Maize-MSW	April 17th	Broadcast applications	33.5-0-0	134	155	April 6th	Insecticide	Seed coating	-	Thiametoxam (3.5 g cL-1)	60	0
		April 17th		0-45-0	440		May 15th	Herbicide	Sprayer localized on high weed pressure zones	5	2.4-MCPA (350 g L-1)	53	0.07
		May 31st		46-0-0	240		May 29th	Herbicide	Localized sprayer on row crop cultivator	35	S-Metolachlore (960 g L-1)	672	0.34
							June 11th	Herbicide	Localized sprayer on row crop cultivator	25	Nicosulfuron (40 g L-1) + Mesotrione (100 g L-1)	21 + 52	0.5
2013	MM_{Conv}	October 21st	Broadcast application	Lime (0-0-0 30%CaO - 21%MgO)	1500	96	April 23rd	Insecticide	Seed coating	-	Thiametoxam (3.5 g cL-1)	59	0
		April 23rd	Localized on the row at sowing	18-46-0	200		April 23rd	Molluscicide	Microgranulator at sowing	100	Metaldehyde (50 g kg-1)	200	0
		June 28th	Broadcast application	46-0-0	130		May 7th	Herbicide	Sprayer	100	S-Metolachlore (960 g L-1)	1344	0.65
							June 5th	Herbicide	Sprayer	100	Nicosulfuron (40 g L-1) + Mesotrione (100 g L-1)	60 + 150	2
	MM_{LI}	October 21th	Broadcast application	Lime (0-0-0 30%CaO - 21%MgO)	1500	87	April 15th	Herbicide	Sprayer	100	Glyphosate (360 g L-1)	1440	0.8
		April 24th	Localized on the row at sowing	18-46-0	200		April 24th	Insecticide	Seed coating	-	Thiametoxam (3.5 g cL-1)	62	0
		June 28th	Broadcast application	46-0-0	110		June 14th	Herbicide	Localized sprayer on row crop cultivator	40	Nicosulfuron (40 g L-1) + Mesotrione (100 g L-1)	24 + 59	0.8
							April 25th	Herbicide	Sprayer	100	Glyphosate (360 g L-1)	1440	0.8
	MM_{CT}	October 21st	Broadcast application	Lime (0-0-0 30%CaO - 21%MgO)	1500	82	May 6th	Insecticide	Seed coating	-	Thiametoxam (3.5 g cL-1)	62	0
		May 6th	Localized on the row at sowing	18-46-0	200		May 6th	Molluscicide	Microgranulator at sowing	100	Metaldehyde (50 g kg-1)	200	0
		June 28th	Broadcast application	46-0-0	100		May 7th	Herbicide	Sprayer	100	S-Metolachlore (960 g L-1)	1344	0.65
							June 14th	Molluscicide	Distributor	100	Metaldehyde (50 g kg-1)	250	0
							June 28th	Herbicide	Sprayer	100	Nicosulfuron (40 g L-1) + Mesotrione (100 g L-1)	60 + 150	2
	Maize-MSW	October 21th	Broadcast application	Lime (0-0-0 30%CaO - 21%MgO)	1500	87	April 24th	Insecticide	Seed coating	-	Thiametoxam (3.5 g cL-1)	62	0
		April 24th	Localized on the row at sowing	18-46-0	200		April 24th	Herbicide	Localized sprayer on seeder	35	S-Metolachlore (960 g L-1)	470	0.3
		June 28th	Broadcast application	46-0-0	110		June 26th	Herbicide	Sprayer	100	Nicosulfuron (40 g L-1) + Mesotrione (100 g L-1)	60 + 150	2

		Irrigation management		Winter covercrop					Mechanical weeding	
Year	**System**	**Start and end**	**Total amount (mm)**	**Sowing date**	**Species (rate in kg ha-1)**	**Sowing machine**	**Destruction date**	**Destruction mode**	**Dates**	**Tool used**
2011	**MM_{Conv}**	May 19th - September 7th	250	-	Bare soil	-	-	-	-	-
	MM_{LI}	May 19th - August 25th	220	May 26th	*Lolium hybridum (10) + Trifolium pratense (10)*	Delimbe seeder fixed on the row crop cultivator	February 24th 2012	Ploughing	May 24th May 26th	Rottary hoe Row crop cultivator
	MM_{CT}	May 19th - August 25th	220	October 10th	*Avena strigosa (30) + Vicia sativa (25) + Phacelia Tanacetifolia (5)*	Cereal seeder Sulky Tramline SE	March 9th 2012	Glyphosate (see Pesticide application section)	-	-
	Maize-MSW	May 19th - August 25th	220	October 10th	*Avena strigosa (50)*	Cereal seeder Sulky Tramline SE	December 5th 2011	Ploughing	May 24th June 10th	Rottary hoe Rottary hoe
2012	**MM_{Conv}**	June 20th - September 11th	310	-	Bare soil		-	-	-	-
	MM_{LI}	June 20th - August 22nd	220	May 29th	*Lolium hybridum (9) + Trifolium pratense (9)*	Delimbe seeder fixed on the row crop cultivator	March 21st 2013	Grinding + Glyphosate (3L ha-1) + Superficial tillage	April 18th May 29th	Rottary hoe Row crop cultivator
	MM_{CT}	June 20th - August 22nd	255	September 28th	*Avena strigosa (25) + Vicia sativa (20) + Secale cereale (20)*	Cereal seeder Sulky Tramline SE	April 25th 2013	Glyphosate (see Pesticide application section)	June 21st	Row crop cultivator
	Maize-MSW	June 20th - August 22nd	220	September 28th	*Avena strigosa (60)*	Cereal seeder Sulky Tramline SE	March 21st 2013	Grinding + Ploughing	April 18th May 29th June 11th	Rottary hoe Row crop cultivator Row crop cultivator
2013	**MM_{Conv}**	July 10th - August 28th	205	-	Bare soil		-	-	-	-
	MM_{LI}	July 10th - August 28th	160	June 28th	*Lolium hybridum (9) + Trifolium incarnatum (9)*	Delimbe seeder fixed on the row crop cultivator	March 11th 2014	Ploughing	June 28th	Row crop cultivator
	MM_{CT}	July 10th - August 28th	160	October 23rd	*Vicia faba (120)*	Cereal seeder Sulky Tramline SE	April 24th 2014	Glyphosate (see Pesticide application section)	-	-
	Maize-MSW	July 10th - August 28th	155	October 10th	*Avena strigosa (60)*	Cereal seeder Sulky Tramline SE	March 11th 2014	Ploughing	July 2nd	Row crop cultivator

Matériel supplémentaire n°2

Operation	Cost (€ ha-1)	Sources	Fuel use (L ha-1)	Sources
Moldboard ploughing	19,5	*k*	21,12	*b, c*
Strip-till	17,5	*k*	17,00	*c*
Field cultivator	4,5	*k*	6,69	*e, f*
Rottary harrow	15,0	*k*	7,93	*a, c, e*
Cultipacker	4,5	*k*	6,78	*a, b*
Disking	9,5	*k*	7,08	*a, g, f*
Sowing	13,5	*k*	4,69	*a, d, b*
Row crop cultivator	18,0	*k*	4,00	*a, d, b*
Rotary hoe	6,5	*k*	2,33	*a, e, i*
Broadcast fertilization application	5,0	*k*	4,65	*e, f, h*
Pesticide spraying (including molluscicide)	5,0	*k*	1,66	*a, d, j*
Harvesting	90,0	*k*	17,40	*a, b, d*
Irrigation	20,0	*k*	1,80	*f*

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Input type	Cost (€ kg-1)	Energy use (MJ kg-1)	Sources	GHG emission (kgeqCO2 kg-1)	Sources
Pesticides					
S-Metolachlor	27,5	276,0	*h*	16,50	*a, b, f, l*
Glyphosate	25,0	441,0	*g, h, m*	16,50	*a, b, f, l*
Thiametoxam	included in seed price	312,0	*a, b, c*	22,80	*a, b*
Nicosulfuron	875,0	293,0	*a, b, c*	16,50	*a, b, f, l*
Mesotrione	350,0	350,0	*n*	16,50	*a, b, f, l*
2.4-MCPA	100,0	293,0	*a, b, c*	16,50	*a, b, f, l*
Metaldehyde	106,2	312,0	*a, b, c*	22,80	*a, b*
Seeds					
Avena strigosae	0,64	6,2	*a, i*	0,40	*a*
Corn	7,00	45,3	*a, c, d, g*	3,80	*a*
Lolium hybridum	3,50	44,4	*a*	3,17	*a*
Phacelia Tanacetifolia	1,66	44,4	*a*	3,17	*a*
Secale cereale	0,75	8,7	*a, i*	0,40	*a*
Trifolium pratense	2,40	41,5	*a, g, j*	2,08	*a*
Trifolium incarnatum	2,95	41,5	*a, g, j*	2,08	*a*
Vicia sativa	1,60	17,0	*a, d, k*	0,91	*a*
Vicia faba	0,18	17,0	*a, d, k*	0,91	*a*
Fertilizers					
Nitrogen		54,8	*a, b, c, e*	3,90	*a, b*
Phosphate		10,3	*a, b, c, e*	0,91	*a, b, f*
Potassium		7,0	*a, b, c, e*	0,54	*a, b, f*
Lime		1,0	*a, c, d*	0,35	*a, b, f*
17-17-17	0,54	-		-	
46-0-0	0,43	-		-	
27-0-0	0,43	-		-	
33.5-0-0	0,41	-		-	
18-46-0	0,60	-		-	
0-45-0	0,78	-		-	
Energy					
Fuel	0,80	44,8	*p, q*	3,30	*a, b*

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Input costs determined with the retailers.

II. Matériel supplémentaire – chapitre III - Impacts des systèmes de culture alternatifs à la monoculture de maïs conventionnelle sur la dynamique de la flore adventice et influence de la flore adventice sur le rendement

		Soil preparation			Maize sowing						
Year	**System**	**Tillage - date**	**Tillage depth (cm)**	**Seed bed preparation - dates**	**Sowing date**	**Sowing rate (grains/m²)**	**Distance between rows (cm)**	**Variety - Earliness**	**Sowing depth (cm)**	**Harvest date**	**Residues management type**
2011	**MM_{Conv}**	Moldboard ploughing - March 15th	25	Rotary harrow - March 25th & April 18th Cultipacker - April 18th	April 18th	9	80	Maggi - Late	3,5	October 14th	Chopped at harvest Disking (October 18th)
	MM_{LI}	Moldboard ploughing - March 15th	25	Rotary harrow - March 25th & April 18th Cultipacker - April 18th	April 18th	10,5	80	Shexxpir - Half-early	3,5	October 7th	Chopped at harvest
	MM_{CT}	Strip-till - March 23rd	20	-	April 14th	10,5	80	Shexxpir - Half-early	3,5	October 7th	Chopped at harvest Disking (October 10th)
	Maize-MSW	Moldboard ploughing - March 15th	25	Rotary harrow - March 25th & April 18th Cultipacker - April 18th	April 18th	10,5	80	Shexxpir - Half-early	2,5	October 7th	Chopped at harvest Disking (October 10th)
2012	**MM_{Conv}**	Moldboard ploughing - March 1st	25	Field cultivator - March 16th Rotary harrow - March 30th	April 6th	8,5	80	Maggi - Late	3,5	October 8th	Chopped at harvest Disking (October 9th)
	MM_{LI}	Moldboard ploughing - March 1st	25	Field cultivator - March 16th Rotary harrow - March 30th	April 6th	9,5	80	Shexxpir - Half-early	3,5	September 21st	Chopped at harvest
	MM_{CT}	Strip-till - April 5th	15	-	April 5th	9,5	80	Shexxpir - Half-early	3,5	September 21st	Chopped at harvest Disking (September 27th)
	Maize-MSW	Moldboard ploughing - January 19th	25	Rotary harrow - April 5th	April 6th	9,5	80	Shexxpir - Half-early	2,5	September 21st	Chopped at harvest Disking (September 27th)

	MM_{Conv}	Moldboard ploughing - April 18th	25	Field cultivator - April 22nd Rotary harrow - April 22nd & April 23rd	April 23rd	9,3	80	Maggi - Late	4	October 9th	Chopped at harvest Disking (October 18th)
	MM_{LI}	Field cultivator - April 22nd	10	Rotary harrow - April 22nd	April 24th	9,8	80	Shexxpir - Half-early	4	October 9th	Chopped at harvest
2013											
	MM_{CT}	No-till	0	-	May 6th	9,8	80	Shexxpir - Half-early	4	October 9th	Chopped at harvest Disking (October 18th)
	Maize-MSW	Moldboard ploughing - November 6th	25	Field cultivator - April 22nd Rotary harrow - April 22nd & April 23rd	April 24th	9,8	80	Shexxpir - Half-early	3,5	October 9th	Chopped at harvest Disking (October 18th)
	MM_{Conv}	Moldboard ploughing - March 18th	25	Field cultivator - March 28th Rotary harrow - April 11th	April 14th	9	80	Maggi - Late	4	October 8th	Chopped at harvest Disking (October 9th)
	MM_{LI}	Moldboard ploughing - March 18th	25	Field cultivator - March 28th Rotary harrow - April 11th	April 15th	9,8	80	Shexxpir - Half-early	4	October 8th	Chopped at harvest
2014											
	MM_{CT}	No-till	0	-	April 29th	9,8	80	Shexxpir - Half-early	6	October 8th	Chopped at harvest Disking (October 9th)
	Maize-MSW	Moldboard ploughing - November 28th	25	Field cultivator - March 21th Rotary harrow - April 11th	April 14th	9	80	Shexxpir - Half-early	4	October 8th	Chopped at harvest Disking (October 9th)

	MM_{Conv}	Moldboard ploughing - March 26th	25	Field cultivator - April 3rd Vibrocultivator - April 10th Rotary harrow - April 14th Rotary harrow - April 21st	April 22nd	9,2	80	Maggi - Late	4	October 3rd	Chopped at harvest Disking (October 7th)
	MM_{LI}	Moldboard ploughing - March 26th	25	Field cultivator - April 3rd Vibrocultivator - April 10th Rotary harrow - April 14th Rotary harrow - April 21st	April 22nd	9,8	80	Shexxpir - Half-early	3	October 3rd	Chopped at harvest
2015											
	MM_{CT}	No-till	0	-	April 24th	9,8	80	Shexxpir - Half-early	3	October 3rd	Chopped at harvest Disking (October 7th)
	Maize-MSW	Moldboard ploughing - November 28th	25	Field cultivator - March 26th Vibrocultivator - April 10th Cultivator - April 15th	April 15th	9,8	80	Shexxpir - Half-early	3	October 3rd	Chopped at harvest Disking (October 7th)

		Fertilization application				
ear	System	Dates	Mode	Type of fertilizer (%N-%P-%K)	Fertilizer doses (kg ha-1)	Total Nitrogen fertilization (kg ha-1)
2011	MM_{Conv}	May 5th May 26th	Broadcast applications	17-17-17 27-0-0	412 333	160
	MM_{LI}	May 5th May 26th	Broadcast applications	17-17-17 27-0-0	353 260	130
	MM_{CT}	May 5th May 26th	Broadcast applications	17-17-17 27-0-0	412 260	140
	Maize-MSW	May 5th May 26th	Broadcast applications	17-17-17 27-0-0	353 260	130
2012	MM_{Conv}	April 17th April 17th May 31st	Broadcast applications	33.5-0-0 0-45-0 46-0-0	198 440 240	176
	MM_{LI}	April 17th April 17th May 31st	Broadcast applications	33.5-0-0 0-45-0 46-0-0	134 440 240	155
	MM_{CT}	April 17th April 18th May 31st June 27th	Broadcast applications	33.5-0-0 0-45-0 46-0-0 27-0-0	134 440 240 185	205
	Maize-MSW	April 17th April 17th May 31st	Broadcast applications	33.5-0-0 0-45-0 46-0-0	134 440 240	155
2013	MM_{Conv}	October 21st April 23rd June 28th	Broadcast application Localized on the row at sowing Broadcast application	Lime (0-0-0 30%CaO - 21%MgO) 18-46-0 46-0-0	1500 200 130	96
	MM_{LI}	October 21th April 24th June 28th	Broadcast application Localized on the row at sowing Broadcast application	Lime (0-0-0 30%CaO - 21%MgO) 18-46-0 46-0-0	1500 200 110	87
	MM_{CT}	October 21st May 6th June 28th	Broadcast application Localized on the row at sowing Broadcast application	Lime (0-0-0 30%CaO - 21%MgO) 18-46-0 46-0-0	1500 200 100	82
	Maize-MSW	October 21th April 24th June 28th	Broadcast application Localized on the row at sowing Broadcast application	Lime (0-0-0 30%CaO - 21%MgO) 18-46-0 46-0-0	1500 200 110	87

	MM_{Conv}	June 6th June 19th	Broadcast application Localized on the row	46-0-0 46-0-0	239 39	170
	MM_{LI}	April 15th June 5th July 19th	Localized on the row at sowing Broadcast application Localized on the row	18-46-0 46-0-0 46-0-0	180 174 87	152
2014						
	MM_{CT}	April 29th June 5th June 27th	Broadcast application Broadcast application Localized on the row	18-46-0 46-0-0 46-0-0	200 174 190	203
	Maize-MSW	April 14th June 5th July 19th	Localized on the row at sowing Broadcast application Localized on the row	18-46-0 46-0-0 46-0-0	180 174 87	152
	MM_{Conv}	April 22nd June 15th	Localized on the row at sowing Localized on the row	18-46-0 46-0-0	180 326	182
	MM_{LI}	April 22nd June 15th	Localized on the row at sowing Localized on the row	18-46-0 46-0-0	180 260	152
2015						
	MM_{CT}	April 24th June 15th	Localized on the row at sowing Localized on the row	18-46-0 46-0-0	180 260	152
	Maize-MSW	April 15th June 15th	Localized on the row at sowing Localized on the row	18-46-0 46-0-0	180 260	152

		Pesticide applications						
ear	System	Dates	Type of product	Mode	Surface treated (%)	Active molecules composition (concentration)	Dose applied per active molecule per hectare (g)*	Value of the operation (HTFI)
2011	MM_{Conv}	April 18th	Insecticide	Seed coating	-	Thiametoxam (3.5 g cL-1)	57	0
		May 5th	Herbicide	Sprayer	100	S-Metolachlore (960 g L-1)	1340	0.65
		May 5th	Molluscicide	Mixed with fertilizer	100	Metaldehyde (50 g kg-1)	75	0
	MM_{LI}	April 18th	Insecticide	Seed coating	-	Thiametoxam (3.5 g cL-1)	66	0
	MM_{CT}	April 5th	Herbicide	Sprayer	100	Glyphosate (360 g L-1)	1800	1
		April 18th	Insecticide	Seed coating	-	Thiametoxam (3.5 g cL-1)	66.2	0
		May 5th	Herbicide	Sprayer	100	Nicosulfuron (40 g L-1)	55	0.96
	Maize-MSW	April 18th	Insecticide	Seed coating	-	Thiametoxam (3.5 g cL-1)	66	0
2012	MM_{Conv}	April 6th	Insecticide	Seed coating	-	Thiametoxam (3.5 g cL-1)	54	0
		April 17th	Molluscicide	Mixed with fertilizer	100	Metaldehyde (50 g kg-1)	150	0
		May 3rd	Herbicide	Sprayer	100	Mesotrione (40 g L-1) + S-Metolachlore (400 g L-1)	150 + 1500	1
		June 1st	Herbicide	Sprayer	100	Nicosulfuron (40 g L-1) + Mesotrione (100 g L-1)	50 + 150	1.83
	MM_{LI}	April 6th	Insecticide	Seed coating	-	Thiametoxam (3.5 g cL-1)	60	0
		May 9th	Molluscicide	Distributor	100	Metaldehyde (50 g kg-1)	200	0
		May 16th	Herbicide	Sprayer	100	Mesotrione (100 g L-1)	150	1
		June 11th	Herbicide	Localized sprayer on row crop cultivator	25	Nicosulfuron (40 g L-1) + Mesotrione (100 g L-1)	15+38	0.50
	MM_{CT}	March 15th	Herbicide	Sprayer	100	Glyphosate (360 g L-1)	720	0.4
		April 5th	Insecticide	Seed coating	-	Thiametoxam (3.5 g cL-1)	60	0
		April 23rd	Herbicide	Sprayer localized on high weed pressure zones	40	Glyphosate (360 g L-1)	288	0.18
		May 3rd	Herbicide	Sprayer	100	Mesotrione (40 g L-1) + S-Metolachlore (400 g L-1)	150 + 1500	1
		May 9th	Molluscicide	Distributor	100	Metaldehyde (50 g kg-1)	200	0
		June 1st	Herbicide	Sprayer	100	Nicosulfuron (40 g L-1) + Mesotrione (100 g L-1)	50 + 150	1.83
	Maize-MSW	April 6th	Insecticide	Seed coating	-	Thiametoxam (3.5 g cL-1)	60	0
		May 15th	Herbicide	Sprayer localized on high weed pressure zones	5	2.4-MCPA (350 g L-1)	53	0.07
		May 29th	Herbicide	Localized sprayer on row crop cultivator	35	S-Metolachlore (960 g L-1)	672	0.34
		June 11th	Herbicide	Localized sprayer on row crop cultivator	25	Nicosulfuron (40 g L-1) + Mesotrione (100 g L-1)	21 + 52	0.5
2013	MM_{Conv}	April 23rd	Insecticide	Seed coating	-	Thiametoxam (3.5 g cL-1)	59	0
		April 23rd	Molluscicide	Microgranulator at sowing	100	Metaldehyde (50 g kg-1)	200	0
		May 7th	Herbicide	Sprayer	100	S-Metolachlore (960 g L-1)	1344	0.65
		June 5th	Herbicide	Sprayer	100	Nicosulfuron (40 g L-1) + Mesotrione (100 g L-1)	60 + 150	2
	MM_{LI}	April 15th	Herbicide	Sprayer	100	Glyphosate (360 g L-1)	1440	0.7
		April 24th	Insecticide	Seed coating	-	Thiametoxam (3.5 g cL-1)	62	0
		June 14th	Herbicide	Localized sprayer on seeder	35	S-Metolachlore (960 g L-1)	470	0.3
				Localized sprayer on row crop cultivator	40	Nicosulfuron (40 g L-1) + Mesotrione (100 g L-1)	24 + 59	0.7
	MM_{CT}	April 25th	Herbicide	Sprayer	100	Glyphosate (360 g L-1)	1440	0.8
		May 6th	Insecticide	Seed coating	-	Thiametoxam (3.5 g cL-1)	62	0
		May 6th	Molluscicide	Microgranulator at sowing	100	Metaldehyde (50 g kg-1)	200	0
		May 7th	Herbicide	Sprayer	100	S-Metolachlore (960 g L-1)	1344	0.65
		June 14th	Molluscicide	Distributor	100	Metaldehyde (50 g kg-1)	250	0
		June 28th	Herbicide	Sprayer	100	Nicosulfuron (40 g L-1) + Mesotrione (100 g L-1)	60 + 150	2
	Maize-MSW	April 24th	Insecticide	Seed coating	-	Thiametoxam (3.5 g cL-1)	62	0
		April 24th	Herbicide	Localized sprayer on seeder	35	S-Metolachlore (960 g L-1)	470	0.3
		June 26th	Herbicide	Sprayer	100	Nicosulfuron (40 g L-1) + Mesotrione (100 g L-1)	60 + 150	2

2014	MM_{Conv}	April 14th	Insecticide	Seed coating	-	Thiametoxam (3.5 g cL-1)	57	0
		April 14th	Molluscicide	Microgranulator at sowing	30	Metaldehyde (50 g kg-1)	75	0
		April 16th	Herbicide	Sprayer	100	Mesotrione (40 g L-1) + S-Metolachlore (400 g L-1)	150 + 1500	1
		April 29th	Molluscicide	Distributor	100	Metaldehyde (50 g kg-1)	250	0
		May 19th	Herbicide	Sprayer	100	Mesotrione (100 g L-1) + Nicosulfuron (40 g L-1) + Dicamba (480 g L-1)	30+12+96	0.73
		June 4th	Herbicide	Sprayer	100	Mesotrione (100 g L-1) + Nicosulfuron (40 g L-1)	75+30	1
		June 13th	Insecticide	Sprayer	100	Lambda-cyhalothrine (100g L-1)	20	0
		July 3rd	Trichograms	Manual	100	-	-	0
	MM_{LI}	April 15th	Insecticide	Seed coating	-	Thiametoxam (3.5 g cL-1)	62	0
		April 15th	Molluscicide	Microgranulator at sowing	30	Metaldehyde (50 g kg-1)	75	0
		April 15th	Herbicide	Localized sprayer on row crop cultivator	30	Mesotrione (40 g L-1) + S-Metolachlore (400 g L-1)	45 + 450	0.3
		April 29th	Molluscicide	Distributor	100	Metaldehyde (50 g kg-1)	250	0
		July 3rd	Trichograms	Manual	100	-	-	0
	MM_{CT}	April 29th	Insecticide	Seed coating	-	Thiametoxam (3.5 g cL-1)	62	0
		April 29th	Molluscicide	Microgranulator at sowing	30	Metaldehyde (50 g kg-1)	75	0
		April 30th	Herbicide	Sprayer	100	Glyphosate (360 g L-1)	1440	1.33
		June 4th	Herbicide	Sprayer	100	Mesotrione (100 g L-1) + Nicosulfuron (40 g L-1)	75 + 30	0.5
		June 20th	Herbicide	Sprayer	100	Tembotrione (200 g kg-1) + isoxadifen-éthyl (100g kg-1)	100 + 50	1
		July 3rd	Trichograms	Manual	100	-	-	0
	Maize-MSW	April 14th	Insecticide	Seed coating	-	Thiametoxam (3.5 g cL-1)	57	0
		April 14th	Herbicide	Localized sprayer on row crop cultivator	30	Mesotrione (40 g L-1) + S-Metolachlore (400 g L-1)	45 + 450	0.3
		April 29th	Molluscicide	Distributor	100	Metaldehyde (50 g kg-1)	250	0
		July 3rd	Trichograms	Manual	100	-	-	0
2015	MM_{Conv}	April 22nd	Insecticide	Seed coating	-	Thiametoxam (3.5 g cL-1)	58	0
		April 22nd	Molluscicide	Microgranulator at sowing	30	Metaldehyde (50 g kg-1)	75	0
		April 24th	Herbicide	Sprayer	100	Mesotrione (40 g L-1) + S-Metolachlore (400 g L-1)	150 + 1500	1
		July 19th	Herbicide	Sprayer	100	Mesotrione (100 g L-1) + Nicosulfuron (40 g L-1) + Dicamba (480 g L-1)	100 + 30 + 288	2.17
	MM_{LI}	April 22nd	Insecticide	Seed coating	-	-	62	0
		April 22nd	Herbicide	Sprayer on the seeder	30	Mesotrione (40 g L-1) + S-Metolachlore (400 g L-1)	45 + 450	0.3
		May 26th	Herbicide	Sprayer on the row crop cultivator	30	Mesotrione (100 g L-1) + Nicosulfuron (40 g L-1)	30 + 9	0.35
	MM_{CT}	April 24th	Insecticide	Seed coating	-	Thiametoxam (3.5 g cL-1)	62	0
		April 24th	Molluscicide	Microgranulator at sowing	30	Metaldehyde (50 g kg-1)	75	0
		April 30th	Herbicide	Sprayer	100	Glyphosate (360 g L-1) + 2,4 Dimethylaniline (480 g L-1)	360 + 1200	1.76
		May 28th	Herbicide	Sprayer	100	Mesotrione (100 g L-1) + Nicosulfuron (40 g L-1)	100 + 30	1.17
		June 19th	Herbicide	Sprayer	100	Mesotrione (100 g L-1) + Nicosulfuron (40 g L-1) + Dicamba (480 g L-1)	100 + 30 + 288	2.17
	Maize-MSW	April 15th	Insecticide	Seed coating	-	Thiametoxam (3.5 g cL-1)	62	0
		April 15th	Herbicide	Sprayer on the seeder	30	Mesotrione (40 g L-1) + S-Metolachlore (400 g L-1)	45 + 450	0.3
		May 28th	Herbicide	Sprayer	100	Mesotrione (100 g L-1) + Nicosulfuron (40 g L-1)	100 + 30	1.17

		Irrigation management		Winter covercrop				Mechanical weeding	
ear	System	Start and end	Total amount (mm)	Sowing date	Species (rate in kg ha-1)	Destruction date	Destruction mode	Dates	Tool used
2011	MM_{Conv}	May 19th - September 7th	250	-	Bare soil	-	-	-	-
	MM_{LI}	May 19th - August 25th	220	May 26th	*Lolium x boucheanum* Kunth *(10)* + *Trifolium pratense* L. *(10)*	February 24th 2012	Ploughing	May 24th May 26th	Rotary hoe Row crop cultivator
	MM_{CT}	May 19th - August 25th	220	October 10th	*Avena strigosa* Schreb. *(30)* + *Vicia sativa* L. *(25)* + *Phacelia tanacetifolia* Benth. *(5)*	March 9th 2012	Glyphosate (see Pesticide application section)	-	-
	Maize-MSW	May 19th - August 25th	220	October 10th	*Avena strigosa* Schreb. *(50)*	December 5th 2011	Ploughing	May 24th June 10th	Rotary hoe Rotary hoe
2012	MM_{Conv}	June 20th - September 11th	310	-	Bare soil	-	-	-	-
	MM_{LI}	June 20th - August 22nd	220	May 29th	*Lolium x boucheanum* Kunth *(9)* + *Trifolium pratense* L. *(9)*	March 21st 2013	Grinding + Glyphosate (see Pesticide application section) + Superficial tillage	April 18th May 29th	Rotary hoe Row crop cultivator
	MM_{CT}	June 20th - August 22nd	255	September 28th	*Avena strigosa* Schreb. *(25)* + *Vicia sativa* L. *(20)* + *Secale cereale* L. *(20)*	April 25th 2013	Glyphosate (see Pesticide application section)	June 21st	Row crop cultivator
	Maize-MSW	June 20th - August 22nd	220	September 28th	*Avena strigosa* Schreb. *(60)*	March 21st 2013	Grinding + Ploughing	April 18th May 29th June 11th	Rotary hoe Row crop cultivator Row crop cultivator
2013	MM_{Conv}	July 10th - August 28th	205	-	Bare soil	-	-	-	-
	MM_{LI}	July 10th - August 28th	160	June 28th	*Lolium x boucheanum* Kunth *(9)* + *Trifolium incarnatum* L. *(9)*	March 11th 2014	Ploughing	June 28th	Row crop cultivator
	MM_{CT}	July 10th - August 28th	160	October 23rd	*Vicia faba* L. *(120)* + *Sorghum bicolor* (L.) Moench *(4)*	April 24th 2014	Glyphosate (see Pesticide application section)	-	-
	Maize-MSW	July 10th - August 28th	155	October 10th	*Avena strigosa* Schreb. *(60)*	March 11th 2014	Ploughing	July 2nd	Row crop cultivator

	MM_{Conv}	May 23rd - September 8th	150	-	Bare soil	-	-	-	-
	MM_{LI}	May 23rd - July 28th	110	June 12th	*Lolium x boucheanum* Kunth *(12)+ Trifolium incarnatum* L. *(9)*	March 26th 2015	Ploughing	May 23rd June 12th	Row crop cultivator Row crop cultivator
2014									
	MM_{CT}	May 25th - July 28th	120	October 15th	*Vicia faba* L. *(120) + Sorghum bicolor* (L.) Moench *(5)*	April 24h 2015	Roller + Glyphosate (see Pesticide application section)	-	-
	Maize-MSW	May 23rd - July 28th	110	-	-	-	-	May 23rd	Row crop cultivator
	MM_{Conv}	May 28th - August 25th	285	-	Bare soil	-	-	-	-
	MM_{LI}	June 5th - August 25th	210	June 18th	*Lolium x boucheanum* Kunth *(6) Trifolium incarnatum* L. *(14)*	-	-	May 26th June 18th	Row crop cultivator Row crop cultivator
2015									
	MM_{CT}	May 28th - August 25th	260	October 9th	*Vicia faba* L. *(120) + Sorghum bicolor* (L.) Moench *(5)*	-	-	-	-
	Maize-MSW	May 28th - August 25th	205	October 9th	*Avena strigosa* Schreb. *(60)*	-	-	June 3rd	Row crop cultivator

III. Matériel supplémentaire – chapitre IV - Impact des systèmes de culture alternatifs à la monoculture de maïs conventionnelle sur l'utilisation des herbicides et la qualité de l'eau

Matériel supplémentaire n°1

System	Clay (<2 µm, g kg^{-1})	Silt ([2;50 µm[, g kg^{-1})	Sand (>50 µm, g kg^{-1})	Organic matter (g kg^{-1})	pH
MM_{Conv}	317±42	405±33	279±75	18.4±0.2	6.2±0.3
MM_{LI}	300±106	406±83	294±190	17.8±2.3	6.4±1.2
MM_{Still}	418±59	402±40	181±18	21.6±2.1	7.1±0.0
MM_{CT}	332±69	429±32	240±100	19.7±0.6	6.8±0.3
Maize-MSW	364±83	426±31	209±91	19.1±2.1	7.1±0.6

Matériel supplémentaire n°2

Year	CS	Total		S-metolachlor		glyphosate		nicosulfuron		mesotrione	
		quantity applied	losses	quantity applied	losses	quantity applied	losses*	quantity applied	losses	quantity applied	losses
2011	MM_{Conv}	1340	0,00%	1340	0,00%	0	_	0	_	0	_
	MM_{LI}	0	_	0	_	0	_	0	_	0	_
	MM_{CT}	928	0,00%	0	_	900	0,00%	28	0,00%	0	_
	MM_{Still}	15	0,00%	0	_	0	_	15	0,00%	0	_
	Maize-MSW	0	_	0	_	0	_	0	_	0	_
2012	MM_{Conv}	925	0,00%	750	0,00%	0	_	25	0,00%	150	0,00%
	MM_{LI}	102	0,02%	0	_	0	_	8	0,33%	94	0,00%
	MM_{CT}	715	0,10%	375	0,13%	252	0,00%	13	0,00%	75	0,28%
	MM_{Still}	471	0,21%	0	_	0	_	7	**5,71%**	0	_
	Maize-MSW	373	0,00%	336	0,00%	0	_	11	0,00%	26	0,00%
2013	MM_{Conv}	777	0,02%	672	0,00%	0	_	30	0,17%	75	0,03%
	MM_{LI}	664	0,00%	157	0,00%	480	0,00%	8	0,00%	20	0,00%
	MM_{CT}	998	0,00%	448	0,00%	480	0,00%	20	0,00%	50	0,03%
	MM_{Still}	813	_	0	_	378	_	0	_	0	_
	Maize-MSW	340	0,00%	235	0,00%	0	_	30	0,00%	75	0,00%
2014	MM_{Conv}	631	0,55%	500	0,21%	0	_	14	**3,69%**	85	**1,17%**
	MM_{LI}	495	0,43%	450	0,42%	0	_	0	_	45	0,67%
	MM_{CT}	515	1,17%	0	_	480	0,06%	10	**18,50%**	25	**15,40%**
	MM_{Still}	501	0,15%	255	0,00%	180	0,04%	12	**4,17%**	38	0,53%
	Maize-MSW	495	0,25%	450	0,23%	0	_	0	_	45	0,44%

Year	CS	dicamba		bentazone	
		quantity applied	losses	quantity applied	losses
2011	MM_{Conv}	0	_	0	_
	MM_{LI}	0	_	0	_
	MM_{CT}	0	_	0	_
	MM_{Still}	0	_	0	_
	Maize-MSW	0	_	0	_
2012	MM_{Conv}	0	_	0	_
	MM_{LI}	0	_	0	_
	MM_{CT}	0	_	0	_
	MM_{Still}	0	_	464	0,12%
	Maize-MSW	0	_	0	_
2013	MM_{Conv}	0	_	0	_
	MM_{LI}	0	_	0	_
	MM_{CT}	0	_	0	_
	MM_{Still}	0	_	435	_
	Maize-MSW	0	_	0	_
2014	MM_{Conv}	32	**2,92%**	0	_
	MM_{LI}	0	_	0	_
	MM_{CT}	0	_	0	_
	MM_{Still}	16	0,00%	0	_
	Maize-MSW	0	_	0	_

Year	CS	Total		S-metolachlor		glyphosate		nicosulfuron		mesotrione	
		quantity applied	losses	quantity applied	losses	quantity applied	losses*	quantity applied	losses	quantity applied	losses
2016	MM_{Conv}	837	0,00%	750	0,00%	0	_	12	0,00%	75	0,00%
	MM_{LI}	457	0,00%	225	0,00%	0	_	15	0,00%	73	0,00%
	MM_{CT}	461	0,00%	113	0,00%	270	0,00%	12	0,00%	30	0,00%
	MM_{Still}	613	0,02%	113	0,11%	360	0,00%	14	0,00%	55	0,00%
	Maize-MSW	470	0,00%	0	_	360	0,00%	38	0,00%	0	_
2017	MM_{Conv}	978	0,07%	750	0,03%	0	_	8	0,00%	100	0,40%
	MM_{LI}	545	0,04%	495	0,03%	0	_	0	_	50	0,00%
	MM_{CT}	1820	0,01%	1400	0,04%	0	_	40	0,00%	140	0,00%
	MM_{Still}	584	0,06%	165	0,15%	300	0,00%	5	0,31%	33	0,00%
	Maize-MSW	545	0,14%	495	0,06%	0	_	0	_	50	0,90%
2018	MM_{Conv}	1670	0,12%	1500	0,06%	0	_	20	0,00%	150	0,73%
	MM_{LI}	545	0,15%	495	0,10%	0	_	0	_	50	0,60%
	MM_{CT}	575	0,02%	0	_	540	0,00%	10	0,00%	25	0,00%
	MM_{Still}	425	0,00%	0	_	360	0,00%	7	0,00%	58	0,00%
	Maize-MSW	545	0,54%	495	0,26%	0	_	0	_	50	**3,20%**

Year	CS	dicamba		bentazone	
		quantity applied	losses	quantity applied	losses
2016	MM_{Conv}	0	_	0	_
	MM_{LI}	144	0,00%	0	_
	MM_{CT}	36	0,00%	0	_
	MM_{Still}	72	0,00%	0	_
	Maize-MSW	72	0,00%	0	_
2017	MM_{Conv}	120	0,02%	0	_
	MM_{LI}	0	_	0	_
	MM_{CT}	240	0,00%	0	_
	MM_{Still}	80	0,04%	0	_
	Maize-MSW	0	_	0	_
2018	MM_{Conv}	0	_	0	_
	MM_{LI}	0	_	0	_
	MM_{CT}	0	_	0	_
	MM_{Still}	0	_	0	_
	Maize-MSW	0	_	0	_