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Ecological Intensification Through Pesticide Reduction: Weed Control, Weed Biodiversity and Sustainability in Arable Farming

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Abstract Amongst the biodiversity components of agriculture, weeds are an interesting model for exploring management options relying on the principle of ecological intensification in arable farming. Weeds can cause severe crop yield losses, contribute to farmland functional biodiversity and are strongly associated with the generic issue of pesticide use. In this paper, we address the impacts of herbicide reduction following a causal framework starting with herbicide reduction and triggering changes in (i) the management options required to control weeds, (ii) the weed communities and functions they provide and (iii) the overall performance and sustainability of the implemented land management options. The three components of this framework were analysed in a multidisciplinary project that was conducted on 55 experimental and farmer's fields that included conventional, integrated and organic cropping systems. Our results indicate that the reduction of herbicide use is not antagonistic with crop production, provided that alternative practices are put into place. Herbicide reduction and associated land management modified the composition of in-field weed communities and thus the functions of weeds related to biodiversity and production. Through a long-term simulation of weed communities based on alternative (?) cropping systems, some specific management pathways were identified that delivered high biodiversity gains and limited the negative impacts of weeds on crop production. Finally, the multi-criteria assessment of the environmental, economic and societal sustainability of the 55 systems suggests that integrated weed management systems fared better than their conventional and organic counterparts. These outcomes suggest that sustainable management could possibly be achieved through changes in weed management, along a pathway starting with herbicide reduction.

Keywords Agroecology · Cropping system · Herbicide · Indicators · Crop production · Biotic interactions

Introduction

Agriculture is facing the challenge to ensure global food security and balance this with minimal impacts on the environment (Foley et al. 2005). Over the last decade, the concept of ecological intensification has been presented as an alternative approach for mainstream agriculture to meet these challenges. Ecological intensification aims at designing productive, sustainable agricultural systems that save on inputs and are less harmful to the environment, notably through the integration of services delivered by biodiversity into crop production and the manipulation of biotic interactions (Doré et al. 2011; Bommarco et al. 2013; Gaba et al. 2014). It thus promotes, amongst other options, the implementation of management strategies that preserve higher biodiversity, decrease the use of anthropogenic inputs and maintain or increase yield levels (Garnett et al. 2013). Amongst the many biodiversity components of agriculture, weeds are an interesting model for exploring

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management options that may lead to a potential ecological intensification in arable farming. Weeds can potentially cause severe crop yield losses when not sufficiently controlled to limit future weed infestations (Oerke 2006; Storkey and Cussans 2007). Yet, they provide habitat resources and are at the basis of food webs in agroecosystems (Marshall et al. 2003; Bohan et al. 2013). As such, weeds greatly contribute to the functioning of agroecosystems (Navas 2012) and are associated with a number of services to agriculture, including crop pollination (Holzschuh et al. 2008) and pest control (Crowder and Jabbour 2014). Exploring ecological intensification through the case of weeds is in addition strongly associated with the generic issue of pesticide use in arable farming, especially herbicides, a topical question that is being raised worldwide (Garnett et al. 2013; Chagnon et al. 2014).

In this paper, we address the potential impacts of substantial reduction in herbicide use on agroecosystem functioning. In our view, herbicide reduction will undoubtedly trigger a number of changes that will concern (i) the land management options required to control weeds, in turn (ii) the weed communities and functions they provide and (iii) the overall performance and sustainability of these management options (Fig. 1).

First, because of the current high reliance on weed chemical control, one may expect that weed abundance would increase, and therefore that some changes in weed management strategies would be required to ensure weed control with less or no herbicide. This implies changes in the cropping systems, i.e. either the combination of the crop sequences or changes in the agricultural practices such

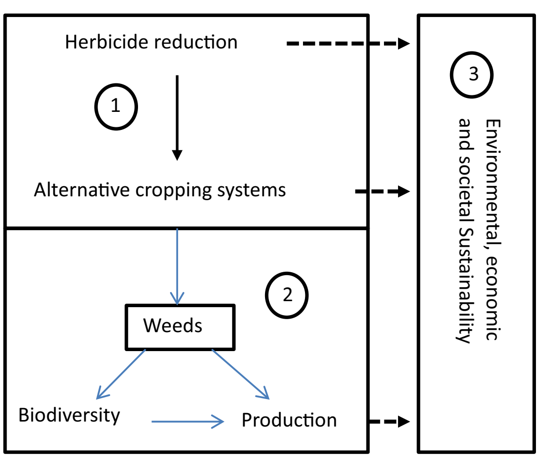

Fig. 1 Framework of the study: herbicide reduction is expected to trigger a number of changes that will concern the management options required to control weeds (1), in turn the weed communities and functions they provide (2); Herbicide reduction, agronomic management options and changes in the weed functions are then expected to impact the overall performance and sustainability of the cropping systems (3)

as soil tillage regime, crop cultivar, sowing date and density, and the introduction of mechanical weeding, or both. These alternative practices are currently implemented in organic and Integrated Pest Management (IPM) systems (Bastiaans et al. 2008; Altieri et al. 2009). Experimental assessments of the long-term reliability of low-herbicide systems for weed control are few, conducted in a limited number of situations, and have led to inconsistent findings (Anderson 2007; Chikowo et al. 2009; Davis et al. 2012). This calls for additional studies on the consequences of herbicide reduction on land management options and long-term weed control.

Second, herbicide reduction which is associated with changes in crop management is likely to alter a number of properties of weed communities. These properties include not only the weed density or weed species richness, but also the overall composition of communities and thus the associated weed functional traits (Ulber et al. 2009; Gunton et al. 2011; Fried et al. 2012). We believe that exploring the functional consequences of the changes in the arable flora that are likely to result from herbicide reduction and associated management options is a key step. More specifically, it appears crucial to address the implications in terms of the services delivered by weeds, i.e. crop production, pollination, pest control or biodiversity.

Finally, if management options can be identified that ensure herbicide reduction whilst maintaining crop production and weed biodiversity, we believe that these options will fare quite differently from their high input conventional counterparts for various aspects of environmental, economic and societal sustainability. For example, the substitution of chemicals by mechanical weeding raises questions about an increase of energy consumption and greenhouse gases emissions contributing to global warming (Deytieux et al. 2012). Most sustainability studies addressing pesticide reduction have compared a limited number of experimental prototypes (Reganold et al. 1993; Davis et al. 2012) or compared contrasted conventional and organic systems. We advocate here that the question should be revisited to account for the inherent variability of cropping strategies that enable to achieve pesticide reduction.

The various implications of herbicide reduction have been addressed in a multidisciplinary project in which agronomists and ecologists performed a comprehensive analysis of 55 experimental and commercial systems located in two regions of France. This analysis was conducted through the combined use of field observations and farmers' surveys, long-term modelling of weed communities and associated functions in response to cropping systems as well as a multi-criteria assessment of the overall sustainability of those systems. Results are presented in three sections corresponding to the steps described in the overall framework.

Reaching the Objective of Herbicide Reduction in Arable Systems

Herbicide reduction exposes farmers to a risk of insufficient weed control. The starting point of our framework thus raises an initial question of importance: is it realistic to reduce chemical weed control substantially and ensure sufficient control and if so, what are the alternative management strategies that can be implemented? The range of available management options was explored here through an analysis of weed management strategies designed by farmers and implemented on their farms. The question of the efficacy of weed control in alternative systems was addressed through the monitoring of cropping systems designed by researchers on experimental farms.

Lessons Learnt from Farmers Adapting to a New Agricultural Context

Farmers' adaptations on their farms provide an invaluable source of information about the agronomic strategies that can realistically be implemented to achieve herbicide reduction. The range of management options implemented over a territory of c.a. 450 km^2 devoted to arable farming (the LTER 'Plaine & Val de Sèvre', see http:/www.zaplainevaldesevre.fr/) were analysed to characterize farmers' strategies with regard to herbicide use. These included 7 organic systems, 8 conventional systems and 13 systems under an agri-environmental scheme dedicated to herbicide use reduction (see Study 1a in Table 1; for more information on cropping systems, see Table 5). Each of the 28 farmers was surveyed individually by interview in order to understand the farm structure, the choice of crop rotations and the weed management strategy implemented. Although the motivation for farmers to reduce herbicide use was not a topic explicitly explored during the survey, we detected a diversity of reasons, such as the financial incentive of the AES, the will to reduce the overall financial cost of pesticide in the farm, environmental and health concerns. From here and throughout the paper, herbicide use level is quantified by the TFI, treatment frequency index, i.e. the actual number of treatments and their dose as used by farmers out of full rate registered dose and full field application (OECD 2001; Gravesen 2003). For each treatment, TFI is the ratio of the product of the dose applied and the area of the field sprayed and the product of the registered dose and the total field area. In fields under conventional and agri-environmental schemes, TFI ranged from 0.4 to 3.1. The survey indicated that two main management strategies coexisted in the study area that resulted in substantial herbicide reduction (Boissinot et al. 2011). In the first strategy, TFI was reduced up to 60 % mostly by reducing the number of applications and to a lesser extent by reducing doses. The second strategy combined the reduction of the number of herbicide applications and dose applied (TFI reduced by 30 to 50 %) and the use of several non-chemical weed management measures, leading to cropping systems that were more complex. Non-chemical measures observed in the study area included the diversification of crop rotations, compared to more 'simple' systems characterized by short rotations (3 years) of autumn-sown crops (see Table 5). This diversification is conducted through the introduction of early spring crops (spring cereals, spring peas), late spring crops (sunflower, soya) as well as multiannual crops (alfalfa, ryegrass) that can be grown up to 6 successive years. Crop rotations are thus longer (up to 10 years here) and more complex, with the succession of crops sown at different times of the year (Table 5). Other non-chemical levers that were common in the study area were mechanical weeding and/or the use of successive stale seedbed before sowing. At least in 2010 (the year of the farmer's survey), no major weed outbreak was reported in the 28 systems, suggesting that the management strategies implemented by farmers yielded satisfactory weed control that year. The frequency in the use of curative measures that may have been used during the following years has not been fully assessed in the project. These longer-term effects were however analysed on experimental farms.

Results from Experimental Research

The weed control efficacy of four low-herbicide systems was assessed in the experimental farm INRA-Epoisses (Study 1b in Table 1) on a trial initiated in 2000 and aimed at prototyping cropping systems (Debaeke et al. 2009). Five systems were investigated, a reference 'conventional' system (CS1), objective of which was the maximization production, and four IPM cropping systems defined with different sets of constraints and management options (see Table 5 for a summary of the five systems). CS2 used reduced tillage in the first 6 years (excluding mouldboard ploughing and mechanical weeding) and is under no-till since then (TFI = 1.33). CS3 uses mouldboard ploughing to manage the soil seed bank but excludes in-crop mechanical weeding (TFI = 1.08). CS4 can use all available measures to reduce weed infestation in combination with mechanical weeding and scarce herbicide applications (TFI = 0.78). CS5 was an extreme version of IPM, as no herbicide was used at all. The experimental design included two blocks of five fields (1 block = one field of each cropping system) that differed in terms of crop sequence, i.e. the crop grown in any given year in a given system differed in the two blocks.

Table 1 Synthesis of the cropping systems used in the three sections of the paper

	Moulboard ploughing	Mechanical weeding	Number of systems	Study 1a	Study 1b	Study 2	Study 3
Burgundy (B)							
Conventional (F)	Annual	No	1			1	2
	Occasional	No	2			2	
		Yes	2			2	
	No	No	2			2	
		Yes	1			1	
IPM (E)	Occasional	No	1				1
		Yes	6				6
	No	No	3				3
		Yes	1				1
Organic (E)	Annual	Yes	1				1
Organic (F)	Occasional	Yes	2			2	2
INRA-Epoisses (EF)							
Conventional (E)	Occasional	No	1		1		
IPM (E)	Occasional	No	2		2		2
		Yes	1		1		1
	No	Yes	1		1		1
LTER 'Plaine & Val de Sèvre' (PVS)							
Conventional (F)	Annual	No	2	2		2	2
		Yes	3	3			3
	Occasional	No	2	2		2	2
	No	No	1	1		1	1
Scheme (F)	Annual	Yes	2	2		2	2
	Occasional	No	4	4		1	4
		Yes	5	5		2	5
	No	No	1	1			1
		Yes	1	1		1	1
Organic (F)	Annual	Yes	2	2			2
	Occasional	Yes	3	3		3	3
	No	Yes	2	2		1	2
Total # systems			55	28	5	26	48

Study 1a = farmers' strategy to reach herbicide reduction; Study 1b = long-term experimental trial to reach herbicide reduction; Study 2 = herbicide and weed services; Study 3 = Sustainability assessment of cropping systems. Systems are conventional, IPM (or under agri-environmental scheme to reduce herbicide use) or conventional and conducted in commercial farms (F) or experimental farms (E). They are characterized according to the frequency of moulboard ploughing and the occurrence of mechanical weeding. A summary of the 55 cropping systems is provided in Table 5

In each field, weed species occurrence and density were surveyed at least twice a year within 32 0.36 m^2 plots and yearly density for each weed species was computed as the maximum density reached in each plot for each cultural year and total weed density per year was computed as the sum of densities of individual weed species. Changes in weed richness and density per field were assessed in two ways, (i) a comparison of initial (2000) and final (2010) values of weed metrics and (ii) a trend analysis of weed metrics through time using yearly values between 2000 and 2010.

Initial weed densities varied greatly amongst fields and, for a given cropping system, it was not unusual to detect an increase in one block and a decrease in the other block when comparing initial and final densities (Table 2). Out of the ten fields, three gradual and significant increases in weed density were detected, two of which in CS5, the system banning herbicide (Table 2a). Densities in CS5 did not reach levels that caused production reduction, but it questions the long-term efficacy of this management strategy. Initial weed richness values also greatly varied amongst fields and were particularly low in CS1 and in

Table 2 Changes in the standing weed flora between 2000 and 2010 in the 10 fields of the long-term INRA experiment

System/block		(a) Weed density					(b) Weed richness				
		2000	2010	$p^{§}$	r_{sp} (P value)[†]		2000	2010	$P^{§}$	r_{sp} (P value)[†]	
CS1	A	33.5 ± 45.4	6.9 ± 8.3	**	−0.41	(0.22)	1.6 ± 1.4	0.4 ± 0.6	***	−0.35	(0.31)
	D	5.7 ± 4.5	13.3 ± 25.3	0.45	0.45	(0.18)	1 ± 1.1	0.7 ± 0.8	0.16	−0.13	(0.7)
CS2	A	56.2 ± 64.1	36.5 ± 37.1	0.13	−0.04	(0.9)	4.6 ± 2.2	2.8 ± 2	**	0.13	(0.7)
	D	27.1 ± 38.5	158.6 ± 147	***	0.72	(*)	1.7 ± 1.2	5.8 ± 2.5	***	0.88	(**)
CS3	A	201.2 ± 312	64.2 ± 32.6	*	0.26	(0.46)	7.8 ± 2.4	6.8 ± 2.2	0.09	−0.03	(0.93)
	D	34.1 ± 21.6	58.7 ± 109	0.19	0.34	(0.32)	5.3 ± 2.3	4 ± 2	*	0.07	(0.82)
CS4	A	29 ± 40.5	128.7 ± 104.4	***	0.5	(0.17)	2.6 ± 1.5	5.4 ± 2	***	0.35	(0.35)
	D	88.5 ± 75.1	60.2 ± 38.5	0.06	−0.06	(0.85)	6.3 ± 1.4	6.6 ± 2.1	0.62	−0.03	(0.93)
CS5	A	4 ± 2.2	123.7 ± 109.2	***	0.66	(*)	0.9 ± 0.8	4.1 ± 1.3	***	0.41	(0.22)
	D	4.2 ± 2	147.7 ± 68.8	***	0.84	(**)	0.4 ± 0.7	7.2 ± 2.1	***	0.84	(**)

There are two fields (A and D) for each of the cropping system (CS1 to CS5, see description in the text). Weed density and richness are average values per field calculated from values recorded in 32 60 × 60 cm vegetation plots within each field

* $p < 0.05$; ** $p < 0.001$; *** $p < 0.0001$

§ ANOVA on data collected in 2000 and in 2010

† Spearman's correlation coefficient between annual values of weed metrics from 2000 to 2010 and time

CS5 (Table 2b). In 2010, richness remained low or even decreased in CS1 whereas it remained high or was significantly higher in some systems, for example in CS5. Richness significantly increased through time in only two IPM fields, which were also fields where density increased through time.

Assessing longer-term effects of these alternative cropping systems (i.e. >10 years on) can be difficult to achieve empirically for obvious reasons and implies to use modelling predictive tools. These tools can be used to (i) check that the level of weed control remains sufficient in the long run and (ii) assess the effects of potential biodiversity gains and/or shifts in the composition of weed communities on the functions the weeds provide in the agroecosystem.

Herbicide Reduction and the Functions Delivered by Weeds

Modelling the Long-Term Dynamics of Weed Communities in Cropping Systems

Weed community dynamics as a function of cropping system were modelled with the mechanistic model FlorSys, i.e. a "virtual field" where cropping systems can be tested and evaluated for their impact on weed flora, and subsequent consequences on crop production and biodiversity. The model integrates a large number of cropping system elements, including low-herbicide systems, and their interaction with pedoclimate (Colbach et al. 2014; Munier-Jolain et al. 2013; Gardarin et al. 2012). The core of FlorSys is a generic life cycle valid for annual weed species and that are currently parameterized for 16 weed species that are commonly found in annual crops (see Appendix 2). It consists of a succession of life stages interacting with cropping system components. The input variables of FlorSys are the cropping system, daily weather and soil characteristics and the initial weed seed bank. After emergence, crop and weed plants are represented as a 3D individual-based multispecific canopy, with individual heights, diameters and leaf distributions. Light availability results in biomass accumulation and growth whereas shading results in etiolation. At weed maturity, seed production is calculated as a function of biomass and the seeds added to the soil seed bank. Crop yield is derived from estimates of crop seeds exported during harvest. The impact of each cultural technique is broken into individual effects that interact with environmental conditions and weed variables. For instance, tillage buries and excavates seeds, it breaks dormancy and triggers germination but it also uproots seedlings and plants, and covers them with soil. All these effects vary with the tillage tool and depth, tractor speed, soil moisture as well as weed species and stages.

The model has been evaluated with independent field data, showing that crop yields, daily weed species plant and seed bank densities and, particularly, densities averaged over the years are generally satisfactorily predicted and ranked when the dominant regional weed species are amongst the 16 simulated FlorSys species. FlorSys though overestimates weed plant biomass and underestimates weed variables summed over all species because currently only 16 species are parameterized. Consequently, the model was used to compare and rank cropping systems, rather than looking at absolute output values.

Indicators of Functions Associated with the Weed Flora

The daily weed variables predicted by FlorSys were translated into ten indicators that assessed the consequences of weeds on agricultural production and biodiversity. With regard to production, five indicators were developed based on the criteria most frequently listed by farmers: (1) crop yield loss, (2) harvest pollution by weed seeds, stems and leaves, (3) harvesting problems due to green weed biomass blocking the combine, (4) field infestation represented by weed biomass averaged over cropping seasons and (5) increase in take-all disease resulting from interactions between grass weeds and the crop pathogen responsible for take-all disease in cereals (Mézière et al. 2013). The contribution of weeds to biodiversity was assessed by five other indicators. Two indicators estimated the weed contribution to plant biodiversity: (1) species richness, and (2) Pielou's index for species equitability (i.e. ratio of the Shannon diversity index of the community vs. maximum Shannon index) and three indicators accounted for the provision of trophic resources for other organisms (3) the number of weed seeds on the soil surface in autumn and winter weighed by the weed species contribution to the diet of farmland birds (Wilson et al. 1999), (4) the number of lipid-rich seeds on the soil surface in summer to feed insects such as carabids and (5) the number of weed flowers in spring and summer weighed by the weed species contribution to feed domestic bees (Ricou et al. 2014). The detail of the calculation of each of the 10 indicators is fully described in Mézière et al., 2014.

Impact of Herbicide Reduction on Weed Functions

We assessed the effect of TFI on the 10 weed indicators in 26 contrasted cropping systems that included conventional, IPM and organic systems (see Study 2 in Table 1; for a full description of cropping systems, see Table 5 and Mézière et al. 2014). These were 16 of the 28 systems surveyed in the LTER (see previous section) and 10 commercial fields in Burgundy with TFI ranging from 1 to 2.8. Pairwise Spearman's correlations between TFI and the ten weed-impact indicators were calculated in order to examine potential consequences of herbicide reduction on weed functions. Overall, TFI was significantly correlated to five out of the ten weed-impact indicators. Our analysis of the 26 systems suggests that herbicide reduction leads to higher weed species richness ($r = -0.42$, $P < 0.0001$) but has no significant effect on weed infestation ($r = 0002$, $P = 0.9524$). Herbicide reduction also resulted in increased harvest pollution ($r = -0.15$, $P = 0.0163$) and harvesting problems ($r = -0.25$, $P < 0.0001$) but it did not translate into increased yield loss ($r = -0.09$, $P = 0.1579$). Finally, we detected a negative impact of herbicide reduction on pollinator resources ($r = 0.25$, $P < 0.0001$) and on the incidence of take-all disease ($r = 0.65$, $P < 0.0001$). In summary, in current cropping systems, reduced herbicide use did not generally result in increased weed harmfulness for crop production or contribution to biodiversity. Indeed, farmers usually modify their cropping systems to compensate for reduced herbicide use, and in the surveyed systems, the reduction in TFI hid many other changes in cultural practices which also affected weed dynamics.

The values of the 10 indicators for a given cropping system were aggregated into weed-impact profiles (radar with 10 branches) which were used to establish a typology of the 26 surveyed cropping systems. The combination of cultural techniques leading to each indicator profile were identified using regression trees (Fig. 2). One single profile maximized biodiversity and minimized weed harmfulness (profile 5); it resulted from systems with occasional tillage or no-till systems, but its herbicide use was quite high (TFI = 1.73). Another interesting profile (profile 2) combined herbicide reduction (TFI = 0.89) with medium yield loss and was reached by two distinct management strategies, one allowing three tillage operations per year but little herbicide use, and the other with less tillage but higher herbicide input. Although this analysis was conducted on a limited number of cropping systems, it reveals that within this set of 26 existing cropping systems the simulated flora can in some instances be of limited harmfulness for production and deliver biodiversity benefits. It also illustrates that different agronomic pathways can lead to a weed flora exhibiting comparable indicator profiles. In the case of profile 2, increasing tillage frequency to reduce TFI would undoubtedly lead to increased fuel consumption which might cancel the lower energy use for herbicide production. This point illustrates the necessity to evaluate the sustainability of emerging cropping systems on broader criteria than TFI and weed functions.

Herbicide Reduction and the Sustainability of Alternative Cropping Systems

The sustainability assessment of 48 of the 55 cropping systems analysed previously was carried out based on a range of indicators covering economic, environmental and social issues (Table 3). The systems included eight organic, 10 conventional and 30 IPM systems that were

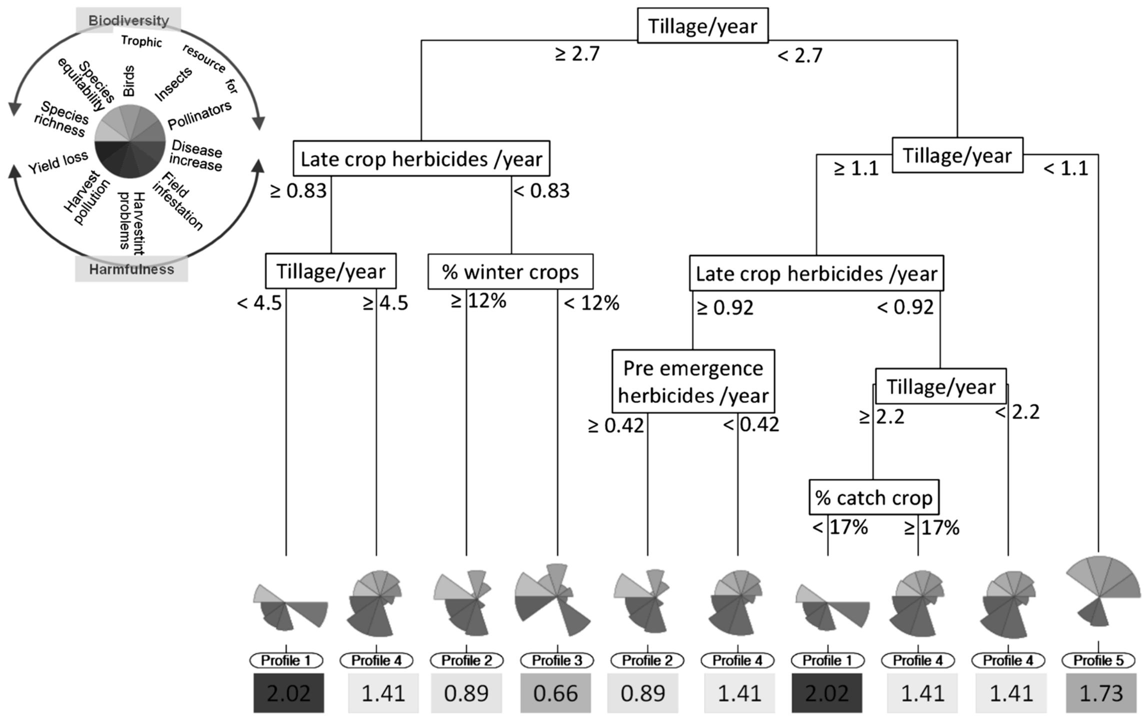

Fig. 2 Typology of surveyed cropping systems based on simulated weed-impact indicators and surveyed management strategies leading to the different performance profiles in terms of weed harmfulness for crop production and weed contribution to biodiversity, with average TFI for each profile (Delphine Mézière © 2015)

located in Burgundy and in the LTER (see Study 3 in Table 1; for a more detailed description of cropping systems, see Table 5 and Lechenet et al. 2014). The aim of the study was to compare the sustainability of these three types of systems. As the performance of a cropping system depends not only on management options, but also on the local production situation, including biophysical and socio-economic local aspects (Aubertot and Robin 2013), indicators of performance and TFI were standardized using a ratio of the performances of the cropping systems over those of a local reference system; reference systems had a clear objective of maximizing production and profit and were selected in order to represent the most widespread crops and practices in a given production situation. For cropping systems set in experimental farms, the local reference was the reference standard system (CS1 in Dijon Epoisses) or the cropping system implemented within the farm before the set-up of the alternative cropping system. For commercial fields, local expert knowledge was used to select one system from the survey, with a standard crop rotation for the area and a crop management representative of local practices.

Relative indicators were averaged per type of system (Conventional, IPM, organic) and statistically compared using a Wilcoxon Mann–Whitney test. The comparison of the performance of the three types of systems is presented in Table 4. This comparison highlights that herbicide use was lower in IPM systems than in conventional systems and thus, so was I-Pest, the indicator of herbicide use impacts. IPM systems also fared better than conventional systems in terms of nitrogen fertilization, energy efficiency and fuel consumption. No significant difference could be found between IPM and conventional systems for energy productivity, semi-net margin, sensitivity to price volatility and workload. Organic systems yielded better environmental performances than IPM systems for herbicide use and impact, nitrogen fertilization and they exhibited a lower sensitivity to price volatility. At the same time, organic systems had a poorer performance than IPM systems for fuel consumption, energy productivity and energy efficiency (Table 4). Profitability (semi-net margin) was not statistically different between the three types of systems; on average, it was lower than in the local 'economically driven' reference system but within each type of system, about a third of the cropping systems were more profitable than their reference systems. Workload was comparable in the three types of systems. Across conventional and IPM systems, we detected no antagonism between TFI and the other eight indicators.

Table 3 Overview of the sustainability indicators

Indicator	Goal	Calculation method	Reference
Herbicide use			
The treatment frequency index (TFI)	Summarizes the level of dependence on herbicides	Estimates the number of herbicide registered doses applied per hectare and per crop season	OECD (2001)
Energy productivity	Compares productivity of different crop rotations	Yields are transformed into an energy metric which corresponds to the amount of energy released per unit of mass by the combustion of the harvested biomass	ADEME (2011)
Energy efficiency	Assesses energy efficiency	Computed from the ratio between productivity and energy consumption. Energy consumption was computed from values for indirect energy consumption associated with the production of farming inputs	ADEME (2011)
Environmental impact			
Fuel consumption	Calculates the fuel consumption due to in-field cropping operation	Estimated according to field cropping operations only, without considering fuel and time consumed for farm-to-field transports. The size and the fuel requirements of the various equipment types are standardized and defined from a national database	BCMA (2012)
Cumulated I-Pest	Measures the risk associated with pesticide application air, surface water and groundwater	Obtained using fuzzy decision trees that allow the aggregation of input variable (e.g. soil, pesticide properties, application date) into an output. Ranges from 0 (no risk) to 1 (full risk) per molecule and cumulated over all pesticide treatments per crop season	van der Werf and Zimmer (1998)
Nitrogen fertilization	Summarizes the level of dependence on exogenous N fertilizers	Calculated from the amount of nitrogen (kg) per surface unit (ha)	
Economic sustainability and workload			
'Semi-net' margin	Assesses the system profitability without subsidies or incentives	In euros, calculated as the gross product per hectare from which we subtracted the input costs (fertilizers, pesticides, seeds, fuel, water and mechanization)	Lechenet et al. (2014)
Sensitivity to price volatility	Measures the ability to generate a stable income in a variable economic context	In euros, the relative standard deviation of the semi-net margin calculated over ten contrasting real price scenarios (crop price, fuel, fertilizers) between 2000 and 2010	(Lechenet et al. (2014)
Workload	Calculates the workload due to in-field cropping operations	Estimated according to cropping operations, without considering extra workload for equipment maintenance or field observations. The working output of the various equipment types were standardized and defined from a national database	BCMA (2012)

Discussion

Herbicide Reduction can be Sustainable

The complementary approaches used in our analysis suggest that herbicide reduction can be reconciled with a long-term control of arable weeds. In our systems, herbicide reduction was achieved through simultaneous decreases in the frequency and the dose used and herbicide use was often considered as one of the diverse suite of tactics that cumulatively ensure weed control (Liebman and Gallandt 1997). The resulting agronomic strategies were thus often more complex and our analysis notably highlights that crop diversification is widely used in IPM (Table 5) where it appears to be an efficient lever to reduce herbicide use and maintain productivity levels (Table 4). This supports the idea that ecosystem services in more diverse cropping systems displace the need for high input levels to maintain crop productivity (Davis et al. 2012). Because they are more complex, IPM systems are often perceived as difficult to implement, with possible bottlenecks in labour organization (Pardo et al. 2010). Here, the feasibility of IPM in

Table 4 Mean value and standard deviation (in brackets) of performance indicators for conventional ($n = 10$ cropping systems), IPM ($n = 30$) and organic ($n = 8$)

Indicator	Conventional	IPM	Organic
TFI Herbicide	0.81 (0.28)^{a}	0.55 (0.25)^{b}	0^{c}
Energy productivity	1.34 (0.60)^{a}	1.02 (0.24)^{a}	0.45 (0.17)^{b}
Energy efficiency	1.1 (0.53)^{ab}	1.26 (0.43)^{b}	0.8 (0.42)^{a}
Cumulated I-Pest	0.81 (0.29)^{a}	0.54 (0.21)^{b}	0^{c}
N fertilization	1.24 (0.36)^{a}	0.75 (0.27)^{b}	0.26 (0.38)^{c}
Fuel consumption	1.07 (0.13)^{ab}	1.01 (0.15)^{b}	1.17 (0.12)^{a}
Semi-net margin	−141.44 (207.72)^{a}	−93.98 (256.35)^{a}	−118.81 (177.54)^{a}
Sensitivity to price volatility	1.38 (0.52)^{a}	1.54 (1.73)^{a}	0.95 (1.21)^{b}
Workload	1.2 (0.21)^{a}	1.08 (0.25)^{a}	1.22 (0.17)^{a}

Indicator values are expressed as a ratio between the cropping system and its local reference system, except for the semi-net margin which is expressed as a difference between the cropping system and its local reference. For each indicator, the difference in mean values between conventional, IPM and organic systems was tested using Wilcoxon Mann–Whitney test and systems followed by an identical letter are not statistically different (derived from Lechenet et al. 2014)

wheat-based rotation was demonstrated experimentally and in farms. Our study also suggests that, usually, there were multiple pathway options available to reach the same objective of herbicide reduction. This means that farmers have some leeway and can choose the management option best adapted to the production objective and constraints of their farm. More importantly, our results indicate that IPM systems showed indications of better performance on the sustainability and environmental criteria tested here compared to other systems. In particular, and unlike organic systems, they delivered levels of productivity that were comparable to conventional systems. This thus challenges the view, widespread amongst farmers that integrated farming equates to reduced and unpredictable productivity (Bastiaans et al. 2008). It also supports the view that IPM outperforms organic farming in terms of land use efficiency, a key issue in the current land sharing—land sparing debate (Phalan et al. 2011; Seufert et al. 2012). Because of their overall high performance, IPM systems thus appear as a promising avenue to achieve widespread herbicide reduction in arable farming. Yet, adoption of these systems would greatly depend on the existence of good markets for the sale of products grown in IPM complex rotations, e.g. in our study the market for *alfalfa*. Poor market conditions are often a bottleneck for the adoption of innovative cropping systems (Corbeels et al. 2014). Ensuring that market conditions for inputs and outputs are in place locally appears to be a necessary step for widespread implementation of IPM low-herbicide systems.

Weeds, Crop Production and Other Services in Low-Herbicide Systems

This study confirms that herbicide reduction and the induced changes in crop management affect the properties of weed communities. Most studies that have documented these changes have compared high input conventional and organic systems in a snapshot, revealing that organic systems usually harbour higher weed species richness (Gabriel et al. 2005; Ekroos et al. 2010; Tuck et al. 2014). Conversely, most studies conducted in IPM have focused on assessing the efficacy of weed control (Chikowo et al. 2009; Davis et al. 2012) and neglected the biodiversity aspect of the arable flora. Here, we considered simultaneously all the aspects and our results suggest that some IPM systems can provide satisfactory weed control, enhance weed biodiversity whilst being economically sustainable. Indeed, despite a general tendency of antagonism between biodiversity and production, some communities observed in the field or simulated by FlorSys provided substantial biodiversity services and caused no negative impacts on crop production. Hence, from this analysis one can conclude that some agronomic pathways allow low-herbicide systems to prevent weed infestation, be productive and generate high weed biodiversity. We believe that our assessment of the weed functions, based on an extensive farmer's survey, reflects quite well the different potential problems that are commonly associated with weeds (Mézière et al. 2014). Conversely, our assessment of weed contribution to biodiversity is probably less comprehensive, as this topic of research is still in its infancy. For instance, our indicators do not integrate the many feedbacks and interactions that occur in agroecosystems, e.g. abundance of generalist predators is correlated to weed seed density (Bohan et al. 2011). These limitations clearly call for additional studies quantifying the functions provided by biodiversity in agroecosystems (Brooks et al. 2012; Storkey et al. 2013) and in turn the services that could be expected from weeds (Bommarco et al. 2013). More, we advocate that such studies should integrate the contribution of the landscape context of specific cropping systems on in-field biodiversity. In the case of arable weeds, the composition, structure and crop management around the focal field is widely recognized to affect the taxonomical and functional richness of weed communities (Petit et al. 2011; 2013; Perronne et al. 2014). Weed communities can also be affected indirectly through landscape effects impacting weed seed predators (Trichard et al. 2013). These elements call for management approaches encompassing multiple spatial scales when implementing ecological intensification in arable farming.

Conclusion

Weed management is often considered as a major obstacle to pesticide reduction in arable farming. Our analysis of the performance of a wide range of cropping systems questions a few pre-conceived notions. It first highlights that the level of herbicide use is not antagonistic with productivity, provided that alternative cropping systems are put into place. More, these innovative systems also appear to fare better than their conventional and organic counterparts when other environmental, economic and societal aspects are considered. Second, our analysis illustrates that herbicide reduction modifies the properties of weed communities and more, our modelling results suggest that some innovative systems have the capacity to reconcile the provision of weed biodiversity services and the limitation of production issues associated with weeds. These outcomes suggest that ecological intensification could possibly be achieved through changes in weed management, along a pathway starting with substantial herbicide reduction. However, there are a number of aspects that need to be addressed for a full validation and before a field application of this general framework. One way forward would be to set-up a long-term interdisciplinary monitoring network of arable fields managed by farmers currently engaging into pesticide reduction and located in different production contexts and landscape settings. Such network could be used to conduct in parallel assessments of the evolution of local and landscape management options, weed flora and communities of other organisms affecting weeds as well as other environmental and social aspects of sustainability not considered in the present study.

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Appendix 1

See Table 5.

Table 5 Summary of the 55 cropping systems used in the study

	Code	Farming type	Number of cultural year per crop type in the rotation					Average number per year over the rotation (management of multiannual crops are excluded from the calculation)			
			E Au	Au	Sp	E Sp	MA	Herbicide TFI	Tillage	Mouldboard ploughing	Mechanical weeding
1	B1	Conv.	1	2				2.80	4.00	0.00	0.67
2	B2	Conv.	1	2		1		2.10	2.00	0.25	0.25
3	B3	Conv.	2	6				1.54	2.88	0.88	0.00
4	B4	Conv.		5	2	1		1.52	3.50	0.38	0.00
5	B5	Conv.	1	2				1.20	4.00	0.33	0.00
6	B6	Conv.		1	1	1		1.10	5.00	0.00	0.00
7	B7	Conv.	1	2				1.00	3.67	0.00	0.00
8	B8	Conv.		2		3		1.00	2.40	0.60	0.20
9	B9	IPM	1	3		1		1.79	3.00	0.00	0.11
10	B10	IPM	1	2		1		1.72	1.39	0.00	0.04
11	B11	IPM	1	3	1			1.46	2.70	0.00	0.00
12	B12	IPM	1	2		3		1.37	0.63	0.75	0.00
13	B13	IPM		5	2	1		1.18	3.13	0.38	0.13
14	B14	IPM		1		1		1.15	3.38	0.00	0.00
15	B15	IPM	1	4	1	1		1.03	2.59	0.41	0.22
16	B16	IPM	1	3	1	1		0.80	2.45	0.59	0.36

Table 5 continued

	Code	Farming type	Number of cultural year per crop type in the rotation					Average number per year over the rotation (management of multiannual crops are excluded from the calculation)			
			E Au	Au	Sp	E Sp	MA	Herbicide TFI	Tillage	Mouldboard ploughing	Mechanical weeding
17	B17	IPM		2	1	2		0.70	2.80	0.80	0.25
18	B18	IPM		3		2	4	0.64	3.86	0.39	0.34
19	B19	IPM		2	2	4		0.59	3.75	0.04	1.63
20	B20	Org.		4	1	3		0.00	3.63	0.88	2.00
21	B21	Org.		4	2			0.00	6.67	0.00	1.83
22	B22	Org.		2	1		3	0.00	2.67	0.33	1.00
23	CS1	Conv.	1	2				2.20	3.50	0.33	0.00
24	CS2	IPM	1	3	1	1		1.33	3.08	0.00	0.00
25	CS3	IPM	2	6	2	2		1.08	3.62	0.46	0.04
26	CS4	IPM	1	3	1	1		0.78	4.25	0.42	2.25
27	CS5	IPM	1	6	1	1	3	0.00	3.86	0.46	2.54
28	PVS1	Conv.					2	3.09	0.50	1.00	0.50
29	PVS2	Conv.		1	2	1		2.71	2.75	0.50	0.00
30	PVS3	Conv.		1	3			2.34	2.75	1.00	0.25
31	PVS4	Conv.			2			2.14	0.00	0.00	0.00
32	PVS5	Conv.			3			1.85	3.00	0.33	0.00
33	PVS6	Conv.		1	2			1.56	2.00	1.00	0.00
34	PVS7	Conv.					1	1.33	0.00	1.00	0.00
35	PVS8	Conv.					1	0.67	1.00	1.00	1.00
36	PVS9	Sche.			5		1	1.74	2.50	0.67	0.00
37	PVS10	Sche.		5		1	4	1.74	1.00	0.60	0.00
38	PVS11	Sche.	1	4		1		1.46	2.50	0.17	0.17
39	PVS12	Sche.		2		1		1.44	0.67	0.00	0.33
40	PVS13	Sche.		1	1	1		1.32	2.00	0.00	0.00
41	PVS14	Sche.	1	4		1		1.26	2.17	0.67	0.17
42	PVS15	Sche.	1	2	1			1.22	1.50	1.00	0.25
43	PVS16	Sche.	1	2		1		1.14	3.00	0.25	0.25
44	PVS17	Sche.	1	2		1	5	1.13	1.71	0.43	0.00
45	PVS18	Sche.		3		1		0.79	2.00	0.75	0.25
46	PVS19	Sche.	1	3		1	5	0.79	2.33	0.83	0.00
47	PVS20	Sche.		1		1		0.78	1.50	1.00	0.50
48	PVS21	Sche.		2		2	6	0.41	1.25	0.63	0.25
49	PVS22	Org.		2	1	1		0.00	5.00	1.00	3.25
50	PVS23	Org.		4	3	1		0.00	3.88	1.00	2.00
51	PVS24	Org.		1		1		0.00	2.00	0.00	1.00
52	PVS25	Org.		1	2			0.00	3.33	0.33	2.00
53	PVS26	Org.		1	1	2		0.00	3.75	0.25	2.50
54	PVS27	Org.		4		2	3	0.00	4.67	1.00	2.33
55	PVS28	Org.		3	2	1		0.00	5.83	0.00	3.33

System code *B* Burgundy, *PVS* LTER Plaine et Val de Sèvre. *TFI herbicide* treatment frequency index, i.e. the number of treatments equivalent to full rates and full field application

Appendix 2

List of the 16 weed species modelled in the FLORSYS model.

Alopecurus myosuroides
Amaranthus retroflexus
Avena fatua
Capsella bursa-pastoris
Chenopodium album
Echinochloa crus-galli
Fallopia convolvulus
Galium aparine
Geranium dissectum
Polygonum aviculare
Polygonum persicaria
Senecio vulgaris
Solanum nigrum
Sonchus asper
Stellaria media
Veronica hederifolia

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