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Diversity is the key for successful agroecological weed management

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ABSTRACT

Reconciling crop productivity and biodiversity maintenance is one of the main challenges of agriculture worldwide. Weed management is recognized to be a key point for ecological intensification in agriculture because weeds can generate severe yield losses but also represent the base of agricultural trophic networks. Research in weed science has often opposed two different perceptions of weeds. Low within-field weed diversity and abundance has either been considered as a sign of efficient weed management or an erosion of the agroecosystem services provided by weeds. However, a recent study in grain-based systems in France highlighted the potential benefits of weed diversity in mitigating crop yield losses. Major yield losses may simply arise from the dominance of a few competitive species. A higher diversity of traits (characteristics) within the weed community should induce complementarity in resource use (light, water, nitrogen *etc.*) and alleviate weed:crop competition. Thus, weed scientists should try to confirm this relationship in different production situations (e.g. floristic contexts, pedoclimates, cropping systems) and then identify cropping systems which promote weed evenness, either from a taxonomic or functional point of view. Weeding operations should exclusively target competitive and dominant species. However, current weed control practices do not allow to target a specific species in a complex community. Therefore, future studies need to identify if weed diversity could rather be indirectly promoted by diversifying weed management tools, which ought to limit weed density/biomass. The CA-SYS platform (INRAE, Dijon, France) is a unique site in Europe to experiment biodiversity-based forms of agriculture, including a diversity of weed management strategies. The overarching objective of the CA-SYS platform is to design and test the feasibility and performances of pesticide-free agriculture which resorts to (cropped and wild) biodiversity in support of production.

INTRODUCTION

Intensive use of herbicides, nitrogen and tillage has generated a massive decline of within-field weed diversity (Albrecht *et al.* 2016). A meta-analysis of 53 studies concluded that weed species richness decreased by 20% on average across Europe after the end of World War II (Richner *et al.* 2015). In Britain, weeds are considered as the most threatened group of plants (Still and Byfield 2007). In France, Fried *et al.* (2009) observed a 42% decline in weed species richness and a 67% decline in total weed density at the field level between 1970 and 2000. This massive decline in weed diversity may be viewed as a sign of efficient weed management and crop productivity maintenance. Weed management is recognized to be a key point for ecological intensification in agriculture (Petit *et al.* 2015) because certain weeds can generate severe yield losses (Oerke 2006), which has justified their control, but also provide ecosystem services beneficial to crop production. However, weed management in arable crops currently mainly relies on herbicides. In France, herbicides represented 43.8% of total pesticides used in 2014 (European Crop protection, http://www.ecpa.eu/). Reducing the reliance of cropping systems on herbicide use is promoted throughout Europe (e.g. EU legislation and French ECOPHYTO plan) since the negative impacts of intensive agriculture on environment and health have been highlighted (Soule *et al.* 1990, Stoate *et al.* 2009). Therefore, there is an urgent need to move towards more sustainable weed management strategies that are much less reliant on herbicide use while preserving crop productivity and biodiversity.

Integrated weed management (IWM) suggests that many different weed management tools can be used in an integrated way to manage weeds while reducing herbicide reliance, which relies on knowledge of cropping system effects on weed dynamics (Swanton *et al.* 2008). Diversified cropping systems integrating a diverse suite of management tools coherently combined at the cropping system scale have been shown to provide efficient long-term weed management while significantly reducing herbicide reliance (Adeux *et al.* 2017, Colbach and Cordeau 2018, Adeux *et al.* 2019a, Yvoz *et al.* 2020). In addition, IWM cropping systems may reconcile agricultural crop production, low herbicide use and weed biodiversity (Petit *et al.* 2015) and be more energy efficient (Lechenet *et al.* 2014, Lechenet *et al.* 2017a). A shift from IWM to agro-ecological or ecologically intensive approaches (Petit *et al.* 2018) should allow to further reduce herbicide reliance. Nevertheless, such a shift will require the status of weeds to be reconsidered (Wilson *et al.* 2009) and a greater understanding of weed:crop interference in complex weed communities (Storkey and Neve 2018). As a matter of fact, the importance of weed diversity in mitigating yield losses has been identified as one of the top five research priorities in current weed science (Neve *et al.* 2018).

Yield loss is due to the dominance of a few competitors

Weeds interact directly with crops by competition for water and mineral resources (Zimdahl 2004), allelopathy (Kadioglu *et al.* 2005) and parasitism (Parker 2009). In weed science, weed:crop interactions have mainly been studied in neighborhood designs considering only two species at a time, *i.e.* the crop and a specific weed species. In such designs, the crop and the weed are grown either together in mixtures or separately in monocultures (Wilson *et al.* 1990, Larson *et al.* 2016). Monocultures allow the assessment of a species maximum productivity in absence of competition (*e.g.* weed-free yield) whereas mixtures encompass the competitive effect of the weed on the crop, and vice versa. The measured outcome is usually plant biomass, considering biomass is strongly related with overall fitness (Weiner 1990). According to ecological theory, weed:crop competition should occur when one of the resources is present in limited supply (Lang and Benbow 2013). Competitive dominants usually express traits related to resource uptake (Novoplansky 2009) and weeds showing competitive trait values tend to generate more biomass and therefore, compete more intensely with the crop (Wilson *et al.* 1990).

Studies focusing on pairwise competitive interactions have provided little insight on the effect of diversified weed communities on crop performance. Indeed, crops are often confronted to a diversity of weed species (Quinio *et al.* 2017, Yvoz *et al.* 2020) which may interact with one another (Clements *et al.* 1994). More recently, increased attention has been paid to the effect of weed diversity in mitigating crop yield losses due to weeds (Pollnac *et al.* 2009, Ferrero *et al.* 2017, Storkey and Neve 2018, Gonzalez-Andujar *et al.* 2019). Adeux *et al.* (2019b) demonstrated in grain-based systems that not all weed communities generate significant crop yield losses and that important crop yield losses were associated to the dominance of a few competitive species capable of producing high levels of biomass (*i.e.* low weed diversity). Out of the six identified weed communities, the authors showed that only four generated significant yield losses (19 to 56%) in unweeded zones. Diversified weed communities limited crop yield losses associated to competitive dominants while potentially maximizing ecosystem services provided by subordinate species.

Low weed diversity may arise because of oversimplified and redundant weed management (**Figure 1**). Recent surveys have shown that the majority of farmers were reluctant to incomplete weed management (Jabbour *et al.* 2014, Kings 2014, Moss 2017), possibly due to a belief of exponential weed dynamics even in diversified IWM systems. Research is needed to highlight that incomplete weeding in a given year can be compensated over time by a diversified crop rotation and a suite of weed management tactics (Adeux *et al.* 2019a). Greater knowledge of weed biology and ecology could allow farmers to better target competitive dominants and ease their fear of the remaining subordinates.

Weed evenness is promoting by cropping system diversity

Farmers dispose of a wide range of options to manage weeds without resorting to herbicides. Weed management tools can be classified in preventive, cultural, mechanical, biological and chemical methods (Barzman *et al.* 2015). Preventive methods focus on keeping weeds out of the field or spreading within a field (*e.g.* composting farmyard manure, cleaning equipment that could transport weed seeds, management of field margins (Cordeau *et al.* 2012),

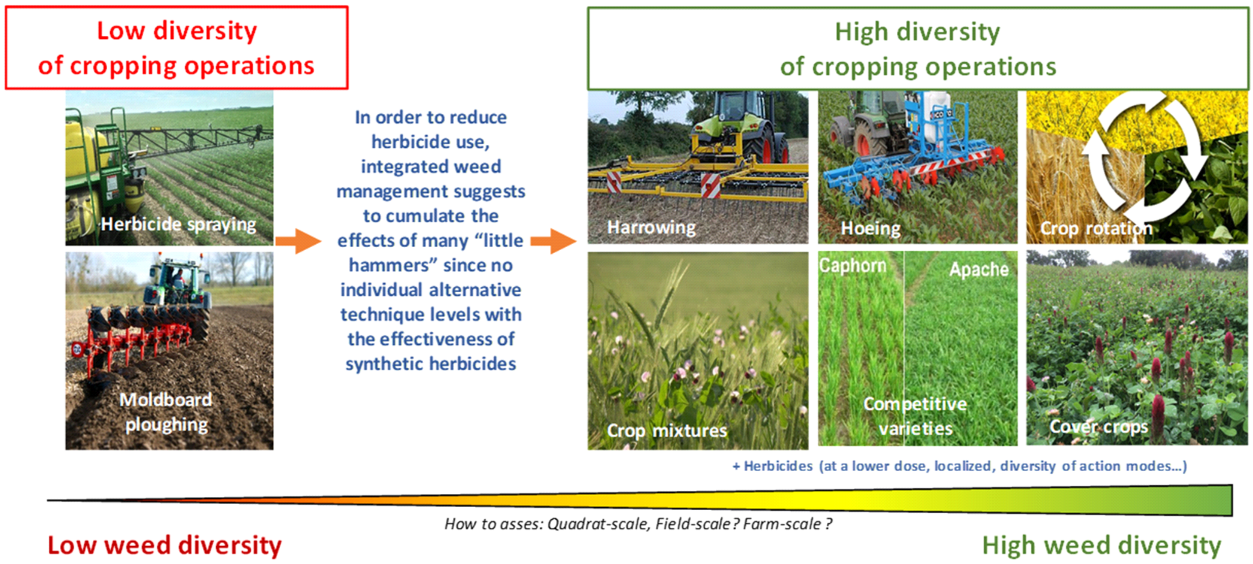

Figure 1. Effects of cropping systems diversification on weed diversity (Copyright: Adeux Guillaume © INRAE 2020)

…). Cultural methods include all practices which can confer the crop a competitive advantage over weeds (*e.g.* crop rotation, increased crop density, optimum nutrient management, delayed sowing, competitive crop cultivars…). Mechanical methods encompass all practices that disrupt germination and destroy the plant (*e.g.* tillage (Cordeau *et al.* 2017), mechanical weeding (Melander *et al.* 2005)…). Chemical methods mainly refer to the direct use of herbicides (*e.g.* timely scouting, proper weed identification, proper conditions of application, rotation of herbicide mode of action…). Biological methods refer to any living organisms used to target weeds (Cordeau *et al.* 2016, Petit *et al.* 2018).

None of these tools allow to match with the effectiveness of synthetic herbicides. Hence, the mere substitution of herbicides by a unique alternative tool is not conceivable. To reduce herbicide reliance and maintain crop productivity, integrated weed management seeks to optimize the synergy between a diverse set of weed management tools coherently combined at the cropping system scale (Swanton and Weise 1991). Sustainable weed management strategies should combine all biological, chemical, cultural, and mechanical methods ("many little hammers") that allow the reduction of weed emergence, weed growth and weed seed production (Liebman and Gallandt 1997). Cropping system diversification can be carried out at both the annual and pluri-annual scales through a diversification of the crop rotation and associated weed management tools (Wezel *et al.* 2014).

Cropping systems which rely on a combination of a well-balanced crop rotation and a diverse set of weed management tools coherently combined at the cropping scale, rather than intensive use of herbicides (*i.e.* one of the main causes in the decline of weed diversity), appear as a promising solution to increase weed diversity while maintaining crop productivity (Ulber *et al.* 2009, Adeux *et al.* 2019a). Increasing crop functional diversity could allow a greater tolerance to weeds in a given year through the prevention of explosive weed dynamics at the cropping system scale (Adeux *et al.* 2019a).

Experimenting pesticide-free biodiversity-based systems

Recent research efforts have led to significant advances on how to manage weeds in agricultural landscapes. For a long time, agronomists have designed and tested cropping systems on long-term cropping system experiments. These cropping system experiments, in contrast to factorial experiments testing one or few practices, aim to design and test the interactive effect of coherent combinations of numerous management factors implemented to fulfill predefined objectives under specific constraints (Drinkwater 2002, Lechenet *et al.* 2017b). Following the same philosophy as cropping system experiments, agroecological system experiments (Petit *et al.* In press) also adopt a systemic approach, but include the design of the spatio-temporal arrangement and management of fields and semi-natural habitats at the farm level. Thus, an agroecological system represents a coherent landscape design strategy: a mosaic of adjacent fields with diverse cropping systems and a network of semi-natural habitats.

Since summer 2018, the CA-SYS platform has been experimenting a diversity of pesticide-free grain-based agroecological systems (wheat, barley, rapeseed, pea, soybean, fababean, *etc.*) on 125 ha divided into 42 plots of 2.5 ha on average (**Figure 2**), within the INRAE 'Domaine d'Epoisses' experimental unit (located close to Dijon, France). The overarching objective of the CA-SYS platform is to design and test the feasibility and performances of pesticide-free agriculture using (cropped and wild) biodiversity in support of production, *i.e.* biodiversity-based forms of agriculture (Cordeau *et al.* 2015). Therefore, all pesticides including those authorized in organic agriculture or bioproducts are also prohibited within the CA-SYS platform.

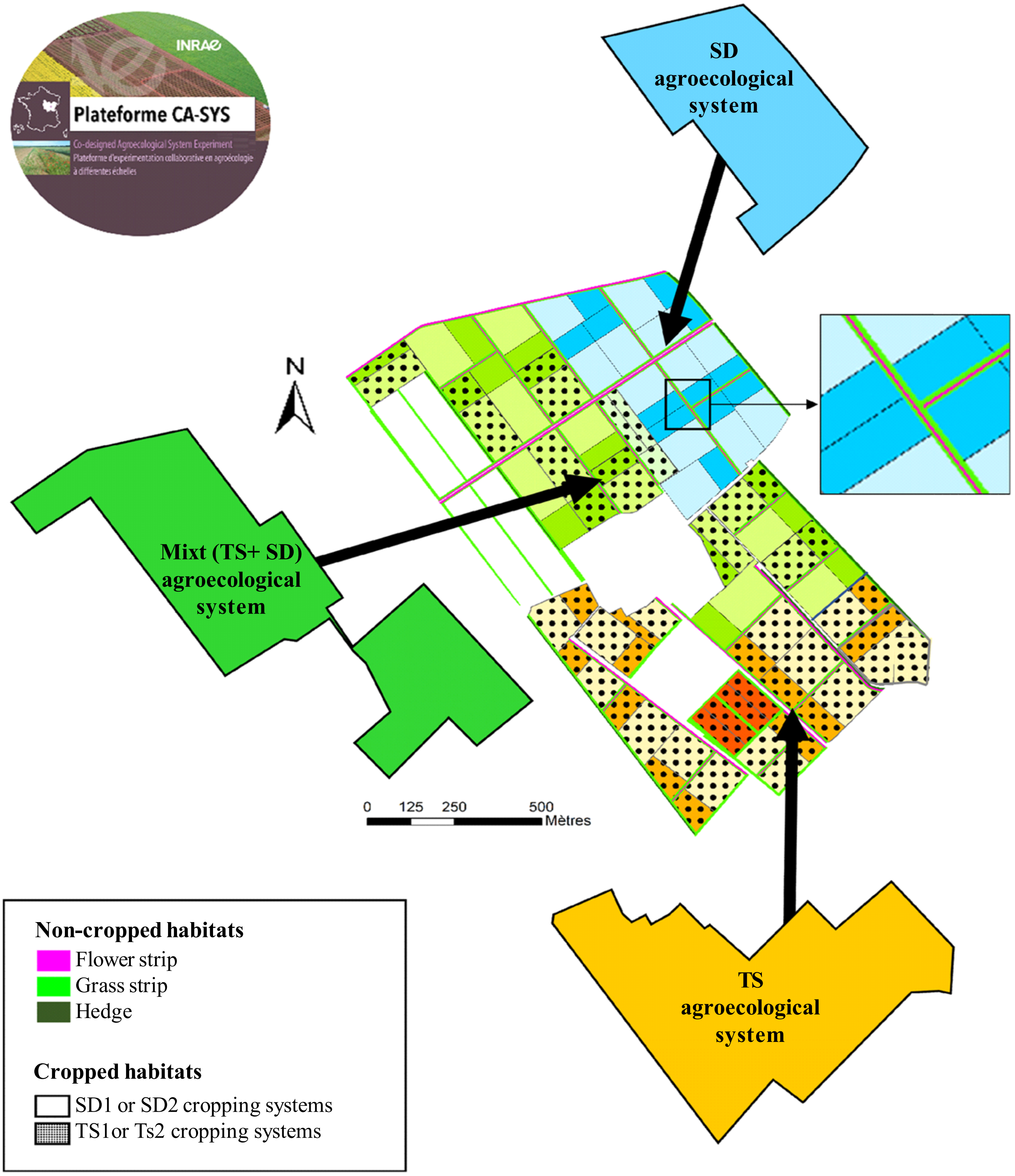

Figure 2. Experimental design of the CA-SYS platform (INRAE, Dijon, FR) testing four pesticide-free cropping systems nested within three agroecological systems (blue: no-till and no-plow systems, orange: plowing-based systems; green: mix of both options) (copyright: Violaine Deytieux and Stéphane Cordeau © INRAE 2020)

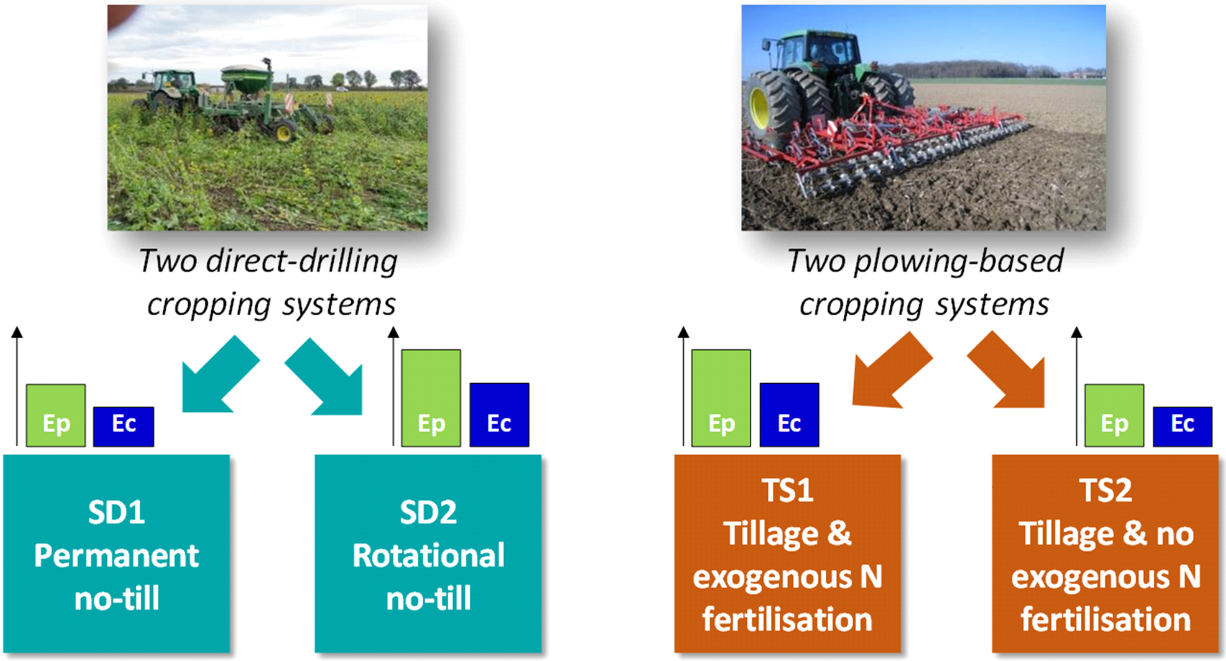

Figure 3. Four pesticide-free cropping systems tested in the CA-SYS Platform (INRAE Dijon, FR) exploring two agricultural pathways. Ep: Energy produced; Ec: Energy consumed to produce. The Ep/Ec ratio is the energy efficiency. (Copyright: Violaine Deytieux and Stéphane Cordeau © INRAE 2020)

The management of each plot is governed by a body of decision rules which vary according to the constraints and objectives assigned to each cropping system. Therefore, the practices are not fixed but adaptive and are implemented following the decision rules according to the observed conditions of the plot (soil humidity, pest pressure, legacy of past crops, etc.). Four pesticide-free cropping systems are tested (**Figure 3**) in line with two relevant agricultural pathways to address agroecological challenges: the first, inspired by organic agriculture, is a plowing-based system (occasional plowing, false seedbed operations, mechanical weeding, hereafter named TS); the other, inspired by conservation agriculture, is a no-plow, direct-seeded system maximizing soil cover (named SD). These two options mobilize a wide diversity of crops in time (at the scale of crop succession) and space (mixtures of species and/or varieties). Within the two pathways (*i.e.* TS and SD), two cropping systems are tested. TS1 allows the use of exogenous N fertilizers whereas TS2 targets auto fertility and bans the use of exogenous N fertilizers. In accordance with the cropping system approach, crop rotation and associated practices differ between TS1 and TS2. SD1 represents a permanent no-till system whereas SD2 allows the use of superficial tillage if necessary, no more than once a year before crop sowing to terminate weeds, crop volunteers or cover crops. No P and K fertilizers are applied in any of the crops of the four cropping systems (i.e. TS1, TS2, SD1 and SD2).

To assess the cropping system and agroecological system performances, study the ecological processes underlying the effect of practices, and describe the transition, the initial state was characterized and observations are performed on a regular basis in fixed zones within plots and semi-natural habitats. For instance, weeds are assessed twice a year in all plots, before and after weeding, and yield loss due to weeds is estimated by biomass sampling of weeds and crops at crop flowering (Adeux *et al.* 2019a).

Conclusion

Weed management is recognized to be a key point for ecological intensification in agriculture. Weeds can generate important crop yield losses. However, yield losses are often due to the dominance of certain highly competitive weed species. High dominance of a few competitors is often due to the oversimplification of cropping systems. Diversifying cropping system both at the spatial and temporal scales ‘keeps weeds guessing’, makes the field an unpredictable habitat for weeds and thus reduces the probability of dominated weed communities, thereby preventing important yield losses. Even if biodiversity-based options to manage weeds exist, there is still an urgent need to design and test ambitious agroecological weed management strategies. The CA-SYS platform is a unique site tackling this challenge, opening avenues for agroecological weed management and should provide insights for future research.

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