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Which cropping systems to reconcile weed-related biodiversity and crop production in arable crops? An approach with simulation-based indicators

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ABSTRACT

Weed management must both control weed harmfulness for crop production and promote weed contribution to biodiversity as an essential component of biodiversity in agricultural landscapes. The objective of the present paper was to evaluate a large range of existing cropping systems to determine management rules for reconciling weed-related biodiversity and weed harmfulness, comparing 26 contrasting cropping systems identified via farm surveys in two contrasting French regions, Burgundy and Poitou-Charentes. These systems were simulated, using the weed dynamics model FlorSys which predicts weed flora dynamics over the years, depending on cropping system and pedoclimate. The simulated flora was translated into five weed harmfulness indicators (crop yield loss, harvest contamination, harvesting difficulty, field infestation, additional crop disease due to weeds) and five weed-related biodiversity indicators (weed species richness and equitability, weed-based trophic offer for birds, insects and pollinators). Cropping system performance was assessed with a Principal Component Analysis (PCA) on the 10 weed-impact indicators, followed by a hierarchical clustering analysis. Five contrasting profiles in terms of weed harmfulness and contribution to biodiversity were identified, combining different levels of weed harmfulness and biodiversity. To identify management strategies (i.e., combinations of cultural practices) for reaching these different performance profiles, tree-based regression and classification models (CART) were constructed to explain performance profiles as a function of cropping system descriptors and pedoclimatic variables. Ten management strategies were identified for reaching the five performance profiles. The most interesting performance profile, which minimized all harmfulness indicators (except harvest contamination and harvesting difficulty) and maximized all biodiversity indicators (except species richness), was reached by a single strategy type, consisting of low or no-till systems. Systems with cover crops and little or no mechanical weeding also reconciled most production and biodiversity goals. Multiple management pathways for reaching a given goal present the advantage of letting farmers choose the strategy most compatible with the objectives and constraints of their farm. The present results were obtained with annual weed species only, and taking into account the management of perennial weeds will probably modify the strategies. The same method was also applied to identify strategies for reconciling crop production, biodiversity and reduced herbicide use, though none of the investigated cropping systems was able to reconcile all three objectives, indicating that novel cropping systems must be designed specifically for this objective.

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1. Introduction

The intensive use of pesticides in agriculture induces dramatic effects on the environment (Matson et al., 1997; Tilman, 1999; Stoate et al., 2001; Geiger et al., 2010). Consequently, crop protection against pests must be rethought in order to drastically reduce its reliance on pesticides while maintaining sufficient crop production (Tilman et al., 2002; Millennium Ecosystem Assessment, 2005). Weeds are a particularly interesting pest model case as they are responsible for the highest potential yield losses (Oerke, 2006), as

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well as an important component of vegetal biodiversity in agricultural landscapes (van Elsen, 2000; Marshall et al., 2003; Le Roux et al., 2008). Moreover, they are also a crucial trophic resource for many other guilds (Marshall et al., 2003; Petit et al., 2011). Thus, cropping systems cannot be solely assessed for their ability to limit weed-related yield loss but must also be evaluated for their potential contribution to biodiversity.

Moreover, cropping systems reconciling both production and biodiversity will probably require an in-depth reorganization of current agricultural practices, modifying and complicating cropping system components as a whole. To identify the best candidate solutions, performing a diagnosis of a large range of existing commercial fields is essential to identify and to rank the most pertinent factors (e.g., Doré et al., 2008; Casagrande et al., 2009; Delmotte et al., 2011) and thus, to develop guidelines for designing new weed management strategies.

Various innovative approaches are currently evaluated in long-term field trials to assess cropping systems and weed flora impact on crop production and biodiversity (e.g., Gerowitt, 2003; Chikowo et al., 2009; Davis et al., 2012) but these can only test a small number of systems in a small number of locations. Farm and field surveys can monitor a larger number of situations but they usually only produce a single “snapshot” of weed flora and other biophysical state variables. Indicators calculated from usual practices and a few pedoclimatic characteristics, instead of direct annual measurements, try to overcome this short-term approach and to consider a larger scale (Bockstaller et al., 2008; Castoldi and Bechini, 2010). Such indicators are though scarce for evaluating weed-related impacts and they were developed assessing floras periodically observed in fields (Franke et al., 2009; Sattler et al., 2010).

Models are increasingly used to overcome these shortcomings. A first evaluation of both weed conservation and weed-induced loss of production was performed with a model of weed growth and competition, demonstrating the potential contribution of weed models to design strategies for weed biodiversity conservation and crop production (Storkey and Cussans, 2007). However, this study was restricted to a short-time assessment, as the employed model only considered part of the weed-life cycle and neglected cultural techniques essential for managing weeds (e.g., tillage). Consequently, in a previous study, we developed a new approach combining a model simulating multispecific weed floras as a function of cropping systems and pedoclimate with a set of indicators assessing the impact of these floras on crop production and biodiversity (Mézière et al., 2015).

The objective of the present paper was to perform a diagnosis of existing contrasted cropping systems identified in farm surveys, using the previously developed simulation-based indicators of weed-related harmfulness and biodiversity, as well as herbicide-use intensity, in order to identify (1) the key components of cropping systems impacting weed-related harmfulness and biodiversity criteria, and (2) cropping system strategies to reach single or multiple objectives of weed management. The weed dynamics model used in the present study was FlorSys (Gardarin et al., 2012; Munier-Jolain et al., 2013, 2014; Colbach et al., 2014b,c) because it is, to the best of our knowledge, to date the only model that (1) not only predicts mean cropping system effects but also their variability as a function of weather and location, which is essential to assess the performance and robustness of cropping systems, and (2) represents weed species as a combination of species traits, which not only makes possible the prediction of cropping system components on weed flora but also the latter’s effect on crop production and biodiversity.

Because weed seeds survive over several years (Gardarin et al., 2010), crop management techniques affect weed dynamics over several years (Liebman and Ohno, 1998; Doucet et al., 1999; Bond and Grundy, 2001; Koocheki et al., 2009; Colbach et al., 2013). Thus, a large number of cropping system determinants must be studied. Moreover, cropping system components are logically and pragmatically combined by the farmer to optimize their effects and interactions as well as their implementation. Their effects on weed-related biodiversity and harmfulness can thus not be investigated with multiple linear regressions as these are not adapted to data with high-order interactions or multi-colinearity (e.g., Davidson and Ramsey, 2000; O’Brien, 2007). Moreover, relationships between explanatory cropping system variables and target variables might not be linear (Tittonell et al., 2008). We thus used the classification and regression tree (CART, Breiman et al., 1984) method to explain weed impact variables from cropping system components. This method was shown to overcome the complexity of numerous interactions between explanatory variables and non-linear relationships between explanatory and target variables (De’ath and Fabricius, 2000; Tittonell et al., 2008; Ferraro et al., 2009; Delmotte et al., 2011).

2. Material and methods

2.1. Panel of studied cropping systems

The diagnosis was performed with a sample of 26 cropping systems, identified from farm surveys in two French areas of arable crop production: 10 were cropping systems identified in Burgundy region (Eastern France) in 2007 and 2009 and, 16 in a long-term monitoring site in Poitou-Charentes (“ZA Plaines & Val de Sèvres”, Western France) (Boissinot et al., 2011; Mézière et al., 2015). In each region, the surveyed farms and fields were chosen to reflect the regional diversity in weed management practices, by varying practices for the main discriminating criteria known to structure weed communities (Zanin et al., 1997; Cardina et al., 2002; Fried et al., 2008, 2012; Gunton et al., 2011): (i) the diversity in crop sowing periods in the rotation (from monocultures to diversified rotations including multiannual crops), (ii) tillage practices (from no tillage to intensive tillage), (iii) chemical weeding intensity (from organic management, i.e., no herbicide, to intensive use of herbicide). Among the 26 cropping systems, six were organic cropping systems. Details are given by Mézière et al. (2015). Surveys consisted in collecting information on all crops (including cover crops) and operations carried out by the farmers during the past years over at least one repetition of the crop succession pattern in one of their field, chosen to be representative of farmer’s main practices.

2.2. Predicting weed communities and their impacts in the surveyed cropping systems

2.2.1. The FlorSys model

FlorSys is a mechanistic (i.e., process-based) model that predicts multi-specific weed dynamics as a function of cropping systems in interaction with pedoclimate. The structure of FlorSys is described in detail in previous papers (Gardarin et al., 2012; Munier-Jolain et al., 2013, 2014; Colbach et al., 2014c) and further information can be found in Section A of the Supplementary material online. The input variables of FlorSys consist in:

- the above-ground climate: evapotranspiration, radiation, temperature and rainfall for each simulated day;
- a description of the simulated location: soil texture and depth as well as latitude;
- the initial weed seed bank (i.e., seed density for each weed species and soil layer) present on the first day of the simulation;
- the cropping system during the whole simulated period, comprising the crop sequence including set-aside and cover crops, the date of all operations (tillage, sowing, herbicide application,

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