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A methodology for multi-objective cropping system design based on simulations. Application to weed management

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ABSTRACT

Weeds are harmful for crop production but important for biodiversity. In order to design cropping systems that reconcile crop production and biodiversity, we need tools and methods to help farmers to deal with this issue. Here, we developed a novel method for multi-objective cropping system design aimed at scientists and technical institutes, combining a cropping system database, decision trees, the "virtual field" model FlorSys and indicators translating simulated weed floras into scores in terms of weed harmfulness (e.g. crop yield loss, weed-borne parasite risk, field infestation), weed-mediated biodiversity (e.g. food offer for bees) and herbicide use intensity. 255 existing cropping systems were simulated with FlorSys, individual indicator values were aggregated into a multi-performance score, and decision trees were built to identify combinations of management practices and probabilities for reaching performance goals. These trees are used to identify the characteristics of existing cropping systems that must be changed to achieve the chosen performance goals, depending on the user's risk strategy. Alternative systems are built and simulated with FlorSys to evaluate their multi-criteria performance. The method was applied to an existing oilseed rape/wheat/barley rotation with yearly mouldboard ploughing from Burgundy which was improved to reconcile weed harmfulness control, reduced herbicide use and biodiversity promotion, based on a risk-minimizing strategy. The best alternative replaced a herbicide entering plants via shoot tips (during emergence) and roots after barley sowing by a spring herbicide entering via leaves, introduced crop residue shredding before cereals and rolled the soil at sowing, which reduced the risk of unacceptable performance from 90% to 40%. When attempting to reconcile harmfulness control and reduced herbicide use, the best alternative changed the rotation to oilseed rape/wheat/spring pea/wheat, replaced one herbicide in oilseed rape by mechanical weeding, delayed tillage before rape and applied the PRE herbicide before oilseed rape closer to sowing. This option reduced the risk of unacceptable performance to 30%. None of the initial or alternative cropping systems succeeded in optimal performance, indicating that more diverse cropping systems with innovative management techniques and innovative combinations of techniques are needed to build the decision trees. This approach can be used in workshops with extension services and farmers in order to design cropping systems. Compared to expert-based design, it has the advantage to go beyond well-known options (e.g. plough before risky crops) to identify unconventional options, with a particular focus on interactions between cultural techniques.

1. Introduction

Weeds are considered to be the most harmful pests among those targeted by pesticides, potentially leading to important crop production losses (Swinton et al., 1994; Oerke, 2006). Weeds can also host and propagate other bioagressors such as pathogen fungi (Wisler and Norris, 2005; Bonin et al., 2013) or parasitic plants (Gibot-Leclerc et al., 2003). Thanks to their efficacy and their relatively simple use, herbicides have been used widely and frequently in arable crops (Eurostat, 2016). As a result, they are now increasingly found in ground and surface water (Barbash et al., 2001; Lopez et al., 2015; Ulrich et al., 2015) and cause health problems (Vinson et al., 2011; Waggoner et al., 2013) while an increasing number of weed species are becoming resistant to a larger range of herbicide mode of actions (Heap, 2016). Moreover, weeds are the most important component of plant biodiversity in agricultural landscapes and contribute to feeding other components of agricultural biodiversity (Marshall et al., 2003; Petit et al., 2011). Consequently, French (http://agriculture.gouv.fr/plan-ecophyto-2015) and European

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legislation (CE) N°1107/2009 aim to restrict herbicide use and available products.

To date no alternative curative weed control technique is as efficient and robust as herbicides. The most frequent alternative, i.e. mechanical weeding, is less or not efficient at all in the crop row, less selective of weed vs. crop plants, often damages weed plants insufficiently and requires several successive operations for sufficient efficacy (Chicouene, 2007). Herbicide-parsimonious weed management strategies need to combine all cropping system components aiming at weed control (Liebman and Gallandt, 1997). Various long-term field trials currently assess innovative cropping systems and weed flora impact on crop production and biodiversity (e.g. Gerowitt, 2003; Chikowo et al., 2009; Davis et al., 2012) but they can only test a small number of systems in a small number of locations. Recently, the DEPHY farm network was set up in France to monitor hundreds of farms over time but with little or no access to biophysical state variables (Pillet et al., 2014). In addition to these methods, *in silico* approaches test a large range of agricultural systems with simulation models to identify those answering to objectives (Loyce and Wéry, 2006). Models allow us to assess many and diverse cropping systems at the long-term and with different weather data for their impact on weed flora (Storkey and Cussans, 2007; Colbach et al., 2014a).

Different approaches exist for model-based cropping system design but all follow the same basic steps (Bergez et al., 2010): (1) generation of candidate cropping systems, (2) simulation, (3) evaluation and selection, and (4) possibly further loops where new candidates are generated based on the first results. If the list of possible candidates is small, then the candidate systems can present the complete list of all possibilities (e.g. a list of crop rotation in ROTAT, Dogliotti et al., 2003; or a list of rotations with herbicide programmes in ECOHERBI, http://ecoherbi.florad.org/; or rotation including cover crop and no till in PRACT, Naudin et al., 2015), but this cannot apply to cropping systems which combine many components with many possible options. Candidate systems are thus often proposed by experts in workshops aiming to design cropping systems (Hossard et al., 2013; Reckling et al., 2016), with the risk of missing innovative approaches that are outside the imagination and expertise of the workshop participants. Optimizing an objective via mathematical or numerical algorithms can overcome this obstacle, e.g. using a linear combination of crop proportions weighted by their agronomical values and penalties for their disadvantages to optimize crop rotations (Schönhart et al., 2011) Cropping system design though is a multi-criteria problem requiring a multi-objective optimization where several objectives and inputs are simultaneously optimized (Ould-Sidi and Lescourret, 2011). Solving optimization problems with complex models is a tedious task requiring to find compromise solutions to integrate antagonisms and synergies between the model performance criteria (deVoil et al., 2006; Groot and Rossing, 2011; Ould-Sidi and Lescourret, 2011; Grechi et al., 2012). Automatic optimization based on algorithms would be difficult in our case because we have to optimize many and often antagonistic objectives as well as many management levers with many options. Moreover, modelling weed dynamics is complex and their simulation is slow. Indeed, weed dynamics must be considered at a multi-annual scale, and a larger number of inputs are necessary to realistically predict them in cropping systems (Colbach, 2010).

Consequently, the objective of the present paper was to develop a method for simulation-based multi-criteria design of cropping systems and to apply it to designing systems reconciling weed harmfulness control, herbicide use reduction and promotion of weed-mediated biodiversity. Instead of an automatic algorithm-based optimization, we propose a manual method that combines the knowledge produced by a large-scale evaluation of existing cropping systems and expert knowledge. The method is aimed at scientists and technical institutes that design agroecological cropping systems. The weed dynamics model used in the present study was FlorSys which is a process-based cropping system model that answers all our requirements, i.e. it predicts the dynamics of a multi-specific weed flora and its impact on crop production and biodiversity (Colbach et al., 2014a).

2. Material and methods

2.1. A short presentation of FlorSys

2.1.1. Weed and crop life cycle

FlorSys is a virtual field on which cropping systems can be experimented and a large range of crop, weed and environmental measurements estimated. The structure of FlorSys is presented in detail in previous papers (Gardarin et al., 2012; Munier-Jolain et al., 2013; Colbach et al., 2014b; Colbach et al., 2014c; Munier-Jolain et al., 2014; Mézière et al., 2015b).

The input variables of FlorSys consist of (1) a description of the simulated field (daily weather, latitude and soil characteristics); (2) all the simulated crops (including cash, undersown, associated, cover and multi-annual crops) and cultivation operations in the field, with dates, tools and options; and (3) the initial weed seed bank which is either measured on soil samples or, more feasible, estimated from regional flora assessments (Colbach et al., 2016). These input variables influence the annual life cycle which applies to annual weeds and crops, with a daily time-step. Pre-emergent stages (surviving, dormant and germinating seeds, emerging seedlings) are driven by soil structure, temperature and water potential. Post-emergent processes (e.g. photosynthesis, respiration, growth, etiolation) are driven by light availability and air temperature. At plant maturity, weed seeds are added to the soil seed bank; crop seeds are harvested to determine crop yield (in t/ha and in MJ/ha). In case of multi-annual crops (e.g. lucerne, ryegrass), seedlings can also be the offspring of vegetative older plants. Perennial weeds are not included in FlorSys.

Life cycle processes also depend on management practices, in interaction with weather and soil conditions on the day the operations are carried out. Herbicides can enter plants via leaves ("foliar"), shoot tips during emergence ("pseudo-root") or roots ("root"). Multiple entry modes are possible. Foliar herbicides only kill emerged weeds on the day of spraying, the other herbicides persist and act over several days and weeks. Systemic herbicides circulate inside the target plant and their efficiency depends less on dosage. FlorSys parameters are currently available for 25 frequent and contrasting weed species. Further details can be found in section A of the supplementary material online.

2.1.2. Domain of validity

FlorSys was evaluated with independent field data from a large range of contrasting cropping systems from several regions and years, including innovative techniques such as conservation agriculture or cover crops as well as those options that were identified as potential solutions in the present study (e.g. fallow mowing, rolling etc). The evaluation showed that daily species densities and, particularly, densities averaged over the years were generally well predicted and ranked in the model's original region, i.e. Burgundy (Colbach et al., 2016). At more southern latitudes, a corrective function was used to keep weeds from flowering during winter. This correction improved prediction quality sufficiently so that FlorSys could be used here to assess cropping systems in terms of weed flora and crop yield.

2.1.3. Assessing weed impacts on crop production and biodiversity

The weed densities simulated by FlorSys are translated into a set of indicators depicting the weed flora impact on crop production and biodiversity (Mézière et al., 2015b; Colbach et al., 2017a) (see section A.4 online). Weed harmfulness indicators consider direct harmfulness for crop production (crop yield loss, harvest pollution by weed debris), technical harmfulness (harvesting problems due to green weed biomass blocking the harvest combine), indirect harmfulness due to pest survival and dispersal by weeds (increase in yield loss due to weed-