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Assessing broomrape risk due to weeds in cropping systems with an indicator linked to a simulation model

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ABSTRACT

Integrated crop protection tolerates residual weed floras if they are not harmful for crop production. These weeds can host harmful crop pests, among which parasitic plants such as branched broomrape (*Phelipanche ramosa*). This holoparasite is responsible for large yield losses in French crops such as oilseed rape. To date, there are no herbicides available to control it. To evaluate *ex ante* the impact of crop management practices on weed-mediated parasite infection of crops, we developed an indicator calculated from outputs of the weed dynamics model FlorSys. It consists of three components assessing weed impact on (1) stimulation of parasite germination during the whole cropping season, i.e. the potential risk reduction for future crops via a reduction of the parasite seed bank, (2) the stimulation of parasite germination in host crops, i.e. the potential risk increase for the current crop, (3) parasite reproduction on weed plants, i.e. the potential risk increase for future crops. This indicator was then used to predict weed-mediated broomrape risk in cropping systems from six regions from France and one from Spain. Antagonisms and synergies with other indicators of weed-harmfulness for crop production and weed contribution to plant and functional biodiversity were investigated with Pearson correlation analyses. For instance, cropping systems with a high parasite risk also had a high functional biodiversity (e.g. weed-based food offer for bees). Effects of crop management practices on the weed-mediated parasite risk indicator were identified with linear models; regression trees were used to identify the combinations of management practices that maximised or minimised weed-mediated broomrape risk. Parasite risk depended on crop rotation, sowing and harvest dates, tillage, herbicides and mechanical weeding. The lowest risk was observed in fields that were last tilled less than 21 days before sowing, with more than 0.6 herbicides per year (i.e. 3 applications in 5 years) with multiple entry modes into the weeds (e.g. leaves and roots) and the last herbicide sprayed no later than 127 days before harvest. RLQ analyses were used to identify correlations between weed species traits (Q matrix) and simulated parasite risk (R matrix), via simulated weed densities (L matrix). Early summer-emerging weed species increased parasite risk. No other notable correlations were found, indicating that parasite risk results from a weed community of interacting species, and not simply from individual weed species. An advice table was built to summarize and explain the effects of crop management practices on weed-mediated parasite risk.

1. Introduction

Weeds potentially lead to important crop production losses (Oerke, 2006; Swinton et al., 1994). Thanks to their efficacy and their relatively simple use, herbicides have been used widely and frequently in arable crops. As a result, they are 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). Consequently, French (http://agriculture.gouv.fr/plan-ecophyto-2015) and European legislation (CE) N°1107/2009 aim to restrict herbicide use.

To date, no alternative weed control technique is as efficient and robust as herbicides. Herbicide-parsimonious weed management strategies combine all cropping system components aiming at weed control (Liebman and Gallandt, 1997) and often tolerate a residual weed flora as long as it does not directly harm crop production. These weeds can host and propagate other crop pests, among which parasitic plants such as branched broomrape (*Phelipanche ramosa* (L.) Pomel). Indeed, *P.*

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ramosa can infect more than 70 weed species in fields and thus persist and even proliferate in the absence of host crops. Potential weed hosts include major broad-leaved weed species of arable crops such as *Capsella bursa-pastoris, Galium aparine, Geranium dissectum, Matricaria perforata, Senecio vulgaris, Sonchus asper* or *Veronica hederifolia*, but no grass weed species (Boulet et al., 2001; Gibot-Leclerc, 2004; Gibot-Leclerc et al., 2003, 2015; Moreau et al., 2016; Simier et al., 2013).

Branched broomrape is a major pest worldwide (Parker, 2013) which causes important yield losses by deriving water and nutrients from its host to survive (Heide-Jørgensen, 2013). In France, *P. ramosa* is particularly damaging to oilseed rape, causing up to 90% yield losses (Gibot-Leclerc et al., 2012). It can infect many other crops such as sunflower, lentils, mustard, pea or lucerne (Fernández-Aparicio et al., 2009; Molenat et al., 2013; Parker and Riches, 1993) which are often used to diversify crop rotations in integrated weed management strategies. Parasite management relies on a combination of practices, each practice being poorly efficient when applied individually (Goldwasser and Rodenburg, 2013; Grenz et al., 2005a; Rubiales et al., 2009). Interactions between *P. ramosa* and weeds make parasite management even more difficult because it has to be reasoned and decided alongside with weed management.

Innovative cropping systems must therefore be evaluated not only for their efficiency in managing harmful weeds, but also for potential side-effects on other pests (Norris, 2005). Simulation models are frequently used to evaluate prospective cropping systems (Bergez et al., 2010; Colnenne-David and Dore, 2015; Jeuffroy et al., 2012; Ould-Sidi and Lescourret, 2011). Indeed, models allow us to assess many and diverse cropping systems in the long term and with different weather data for their impact on weed flora (Colbach et al., 2014a). Detailed process-based models have been developed for non-parasitic weeds (Colbach et al., 2014a) whereas for parasitic plants, only simple population dynamics models are available (Eizenberg et al., 2005, 2012, 2003; Ephrath and Eizenberg, 2010; Grenz et al., 2005a; Hershenhorn et al., 2009; López-Granados and García-Torres, 1997; Manschadi et al., 2001) which do not integrate interactions with non-parasitic weeds. Including these interactions is hampered by insufficient knowledge of the parasite life-cycle (e.g. seed dormancy and survival in soil) and of weed variables required for predicting interactions (e.g. root architecture).

An alternative is to develop indicators of weed-mediated parasite risk. Indicators aggregate existing knowledge and aim to provide information about a variable that is difficult to access in order to help management decisions (Bockstaller et al., 2015, 2008). They can be built from expert opinion and available literature to overcome knowledge gaps that make process-based modelling impossible, and can be connected to process-based models to transform multiple and complex model outputs into scores that are easier to analyse by stakeholders (Mézière et al., 2015b).

Consequently, the objective of the present study was to (1) develop a predictive-effect indicator of weed contribution to branched broomrape epidemics and to connect it to a process-based weed dynamics model, (2) simulate a series of actual and prospective cropping systems to quantify the effects of crop management practices on weed-mediated parasite risk, (3) identify which weed species and traits increase or decrease parasite risk. The weed dynamics model used in the present study was FlorSys which is a process-based cropping system model that predicts the dynamics of multi-species weed floras and their 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 while estimating a large range of crop, weed and environmental measurements (Colbach et al., 2014b,c; Gardarin et al., 2012; Mézière et al., 2015b; Munier-Jolain et al., 2014, 2013).

The input variables of FlorSys consist of (1) a description of the simulated field (daily weather, latitude and soil characteristics); (2) all the simulated crop management operations in the field, with dates, tools and options; and (3) the initial weed seed bank. 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, shade avoidance) 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). Life-cycle processes also depend on management practices, in interaction with weather and soil conditions on the day the operations are carried out.

FlorSys parameters are currently available for 25 frequent and contrasting weed species (Appendix A) and 21 crop species (Appendix B). Further details can be found in section A of the supplementary material online (Appendix C).

2.1.2. Domain of validity

FlorSys was evaluated with independent field data, showing that daily plant and seed densities and, particularly, densities averaged over the years were generally well predicted and ranked depending on the weed species and cropping systems 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.

2.2. Designing an indicator of weed impacts on parasite risk

2.2.1. Principle

FlorSys already includes several indicators that depict the weed flora impact on crop production and biodiversity (Table 1). These indicators are based on the following principles (Mézière et al., 2015b): (1) identification of the relevant weed state variable, e.g. seed density on soil surface for the bird-food indicator, (2) identification of the relevant impact period, e.g. winter for bird food, as the season with the highest famine risk, (3) choice of the relevant species functional traits, e.g. seed lipid content for the carabid-food indicator. Food-offer indicators reflect a potential weed impact, i.e. a potential food offer for fauna; they do not assess an actual service, i.e. whether the target organisms are actually present and benefit from the food offer. Conversely, indicators of plant biodiversity and weed harmfulness illustrate

Table 1
Antagonisms and synergies of weed-mediated parasite risk with other weed impacts on crop production and biodiversity. Pearson correlation coefficients between indicator values averaged over the simulation.

Indicators of weed impact	Parasite risk
Plant biodiversity	
Species richness (number of species)	0.51
Species equitability (Pielou)	0.17
Weed-based trophic resources for	
Birds	0.26
Carabids	0.61
Bees	0.73
Direct harmfulness	
Crop yield loss	0.63
Harvest pollution by weed seeds and debris	0.57
Harvesting problem due to green weed biomass blocking the combine	0.57
Other harmfulness	
Field infestation by weed biomass during crop growth	0.56
Additional take-all disease in cereals[a]	0.03

[a] Take-all disease is a harmful root disease caused by *Gaeumannomyces graminis* var. *tritici* which also infects grass weeds.