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Reduced herbicide use does not increase crop yield loss if it is compensated by alternative preventive and curative measures

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ABSTRACT

Herbicide use must be reduced because of environmental and health issues. This raises the question of whether weeds and the resulting crop yield loss will increase. Previous studies analysing relationships between herbicide use intensity, weeds and yield loss suffer from methodological shortcomings in terms of weed flora and farm diversity as well as temporal scales. Here, we collected data on 272 arable cropping systems from one Spanish and six French regions, from farm surveys, the Biovigilance-Flore network, expert opinion, cropping system trials, crop advisors and scientists. Each system was simulated over 27 years and with 10 weather repetitions consisting of 28 randomly chosen weather years, using the virtual-field model FlorSys. This process-based model simulates multi-species weed floras and crop canopies as a function of cropping systems and pedoclimate at a daily time-step over the years. Four series of simulations were run, 1) starting with a typical regional weed flora, 2) eliminating all herbicides without any other change in management practices. The two series were run again, but without an initial weed seed bank. Comparing series 1 and 2 to respectively 3 and 4 led to calculating a crop yield loss due to weeds in series 1 and 2. Comparing series 1 and 2 quantified the herbicide impact on weeds, crop production and yield loss. The simulations showed that (1) crop yield loss increased with increasing weed biomass, and that the weed/crop biomass ratio at crop flowering was the best indicator of the year's yield loss, (2) herbicide use intensity was not correlated to either weed variables or yield loss, because herbicide use intensity greatly depended on other management practices; e.g., it decreased with increasing frequency and interannual variation of mechanical weeding and superficial tillage, (3) weed biomass and yield loss increased when herbicides were eliminated without any other change in management practices, (4) effects were more visible at the multi-annual than the annual scales. The systems the most sensitive to herbicide suppression were characterized by monotonous rotations with short crop cover, high herbicide use, no plough or winter ploughing and frequent rolling operations. Finally, a decision tree predicting yield loss as a function of management practices was proposed to support farmers and crop advisors when designing innovative cropping systems reconciling low herbicide use and low yield loss.

1. Introduction

The agricultural sector must reduce pesticide use because of environmental and health issues (Stoate et al., 2009; Waggoner et al., 2013). This raises the question of whether agricultural production will be impaired by pests, and particularly weeds. The latter are considered to be the pest the most harmful for crop production when not controlled adequately (Oerke, 2006) but this conclusion is mostly based on experiments that compare annual crop yield in fields with different weed densities (Cousens, 1985; Song et al., 2017), often consisting of a single weed species and a single homogenous emergence cohort (Milberg and Hallgren, 2004). However, fields are usually infested by many contrasting weed species (Fried et al., 2008a), with successive emergence cohorts (Cordeau et al., 2017a,b). To date, few studies have attempted to study deleterious effects of weeds at the community level (Berti and Zanin, 1994; Swinton et al., 1994; Florez et al., 1999). Both single-weed- and community-based studies focused on the direct interference assessing yield losses at the annual scale. However, farmers are often more interested in controlling yield loss over time than in the annual yield loss (Macé et al., 2007), as their production is not so much impaired by the single weed plant they overlooked in a given year but by the increase in yield loss due to hundreds or thousands descendants that a single plant could provide for the subsequent years (Buhler et al., 1997). In addition, they are concerned by other aspects of weed harmfulness, such as harvest contamination by weed seeds and debris, harvesting operations slowed down by green weed biomass, or loss of

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face if fields are infested by weeds (Mézière et al., 2015).

The question therefore is how much weeds impact crop production in actual farmers' fields and cropping systems, and how necessary or exchangeable herbicides are to ensure production. Previous studies attempted to answer this question by surveying weeds and yields in a range of farmers' fields and linking these data with herbicide use (O'Donovan et al., 2005; Gianessi and Reigner, 2007). This approach has the advantage to assess the effect of actual weeds in contrasting pedoclimatic conditions and production situations. But these studies usually present only an annual snapshot, disregarding long-term weed impacts and unable to disentangle the direct effect of cropping systems on yield from their indirect impact via their effect on weeds (Quinio et al., 2017). In addition, farmers adapt their practices to the weed flora they observe in their fields (Wilson et al., 2008), which makes it difficult to separate the effect of cropping systems on weeds from the effect of weed perception by the farmer on actually implemented practices. Moreover, cropping systems are a logical combination of cultural techniques that are optimised depending on farmers' objectives and constraints (Boiffin et al., 2001). As a consequence, the herbicide use intensity in a field depends on the other practices (Clarence and Stephan, 1991), which makes it difficult to separate the effect of herbicides on weeds from the effects these other practices. Herbicide tests circumvent this problem by comparing weed floras in sprayed vs. unsprayed sections of fields (Sweat et al., 1998) but they usually only assess impacts on weeds during a few weeks after treatments. Few of them consider effects on crop production (Milberg and Hallgren, 2004; Soltani et al., 2016), and then only with annual data focusing on one crop, disregarding all long term impacts.

To overcome these methodological problems, we propose to combine surveys of farming practices with model-based simulations to (1) quantify the impact of realistic weed communities on crop production at the annual and multi-annual scale in a range of contrasting pedoclimates and cropping systems, (2) analyse the link between herbicide use intensity and other cultural practices, (3) quantify the impact of herbicide use on weeds and crop production, (4) identify the combinations of cultural practices that are most resilient to herbicide suppression and that minimise yield gaps due to weeds. The analysed cropping systems were provided from several sources (farm surveys, crop advisors, regional statistics, or designed with decision trees) to cover different strategies of designing systems. These systems were tested with a process-based model to mimic real field conditions as closely as possible. Using a model made it possible to run several simulation series to disentangle confusing effects, in the present case herbicide use intensity vs other cultural practices, and weed impacts on crop production vs effects of cultural practices on weeds and crop production.

2. Material and methods

2.1. Principle

The first step consisting in collecting cropping system data from diverse regions and production situations. The data were collected from several sources, using aiming to include (1) past and current farmers' practices based on farmers' interviews, agricultural statistics and regional expertise, (2) innovative systems aiming to reduce herbicide use, based on trials and proposals by crop advisors and scientists. All sources of data presented a gradient in herbicide usage and a diversity of alternative strategies.

The cropping systems were simulated with a virtual-field model. The chosen model had to simulate multi-specific and multi-cohort weed dynamics and their impact on crop production as a function of cropping systems and pedoclimate, at a daily scale over several years or decades. FlorSys (Gardarin et al., 2012; Munier-Jolain et al., 2013, 2014; Colbach et al., 2014a,b, 2017d; Mézière et al., 2015) is the only model answering to these requirements. In addition to direct weed harmfulness (yield loss, harvest contamination), FlorSys predicts indicators of technical (harvesting problems), sociological (loss of face due to field infestation) and indirect harmfulness (promotion of weed-borne crop diseases and parasites) (Mézière et al., 2015; Colbach et al., 2017a). The simulation plan was designed to disentangle confusing effects. Cropping systems were tested twice, with and without weeds, to discriminate the sole impact of weeds on crop production from the effects of cultural practices. To separate the effects of cultural practices on weeds from the reciprocal, practices were not adapted to the predicted weed floras over time. Systems were also simulated with and without herbicides (without any other change in cultural practices) to discriminate the effects of herbicides on weeds and crop production from effects of changes in cultural practices that usually accompany changes in herbicide use.

2.2. The virtual field simulated by FlorSys

2.2.1. 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 measures estimated. The structure of FlorSys is presented in detail in previous papers (Gardarin et al., 2012; Munier-Jolain et al., 2013, 2014; Colbach et al., 2014a,b, 2017d; Mézière et al., 2015). Only a short summary is given here. Further details can be found in Section A of the Supplementary material online.

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 and management 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., 2016a,b). 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. FlorSys is currently parameterized for 25 frequent and contrasting annual weed species (Table 1).

2.2.2. Effect of cultural practices

Life cycle processes also depend on the dates, options and tools of management practices (tillage, sowing, herbicides, mechanical weeding, mowing, harvesting), in interaction with weather and soil conditions on the day the operations are carried out (Section A.3 online). For instance, weed plant survival probabilities are calculated deterministically depending on management operations (tillage, herbicides, mechanical weeding, mowing, harvesting), biophysical environment as well as weed morphology and stage; the actual survival of each plant is determined stochastically by comparing this probability to a random probability. Herbicides can enter plants via leaves ("foliar"), shoot tips during emergence ("pseudo-root") or roots ("root"). Multiple entry modes are possible ("multi-mode"). 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.

2.2.3. Effect of weeds on crop production

FlorSys simulates crop yield as well as a set of indicators assessing weed impact on crop production (Mézière et al., 2015; Colbach et al., 2017a) (see Section A.4 in Supplementary material online). These indicators consider direct harmfulness for crop production (crop yield loss, harvest pollution by weed debris), technical harmfulness