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Modelling crop-weed competition: Why, what, how and what lies ahead?

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A B S T R A C T

Weeds are one of the major constraints to food production in agricultural systems throughout the world, with their main impact being reducing crop yields through competition for water, light, space, and nutrients. Computer simulation modelling provides an important tool for helping to understand and predict crop-weed competition and the role it can play in integrated agricultural systems in increasing crop yields and managing weeds. In this paper we discuss (1) *why* it is useful or important to model crop-weed competition, (2) *what* management options likely to affect crop-weed competition should be addressed with modelling, (3) *how* crop-weed competition and its effects have been modelled, and (4) *what* potential new developments in crop-weed competition modelling *lie ahead*.

1. Introduction

Weeds, undesirable plants interfering with agriculture and natural resources, are one of the major constraints to food production in agricultural systems throughout the world. They increase production cost and negatively affect crop yield by competing for nutrients, sunlight, space, and water. In Australia, for example, weed control methods cost Australian growers 1.5 billion Australian dollars per year and weeds cost 2.5 billion Australian dollars per year in lost agricultural production (Department of Environment, 2016). If left uncontrolled, they can cause severe crop yield losses.

Weeds can be directly controlled by manual weeding, mechanical weeding, or herbicides. The availability of herbicides has allowed a substantial reduction in the amount of labour required in agriculture, and so herbicides are heavily used to manage weeds and lessen crop yield losses due to weed infestation (Chauhan and Gill, 2014). The increased use of herbicides, however, has been accompanied by concerns over the evolution of herbicide resistance in weeds, weed species population shifts, increased costs of herbicides, and environmental pollution (Buhler, 2002; Buhler et al., 2000; Chauhan and Johnson, 2010b). The heavy reliance on herbicides to control weeds, for example, has already led to the evolution of resistance in 249 weed species (144 dicots and 105 monocots) globally (Heap, 2016). These concerns necessitate the need to improve integrated weed management (IWM) programs based on cultural practices (Chauhan, 2012; Chauhan et al., 2012; Liebman et al., 2016). An important component of such IWM programs should be to reduce weed seed set by either making the crop more competitive or making weeds less competitive, thus reducing the effects of weeds on the crop in future (Liebman et al., 2016). Increasing crop competitiveness relative to the weeds may be achieved by reducing row spacing, increasing crop densities, using weed-competitive cultivars, or modifying row orientation. Manipulating the crop row spacing and planting density may close the canopy faster and reduce light interception by weeds and therefore improve weed control (Bàrberi, 2002).

Having crops that compete more effectively with weeds has two main benefits. The most obvious and immediate benefit is probably that if crops compete more effectively then crop yield will be higher

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(as yield loss due to competition is lower). A second benefit, that may be even more important, is that if crops compete more effectively then biomass and hence seed production of the weeds will likely be reduced (Chauhan and Johnson, 2010a). The benefits of reduced weed seed production may not have direct benefits like increased crop yield, but by reducing the weed seed bank, weed populations in future years will be reduced, meaning less reliance on other forms of weed control, such as herbicides. These advantages also need to be balanced against potential disadvantages of a more competitive, such as increased intraspecific competition or microclimatic conditions more suited to pathogens or pests, due to a thicker canopy.

Computer simulation modelling provides an important tool for helping to understand and predict crop-weed competition and the role it can play in integrated agricultural systems in managing weed populations and increasing crop yields. In this paper, we discuss (1) *why* it is useful or important to model crop-weed competition; (2) what management options likely to affect crop-weed competition, either directly or through interactions with environmental conditions, should be addressed with modelling; (3) what kinds of modelling approaches have been used to model crop-weed competition and its effects in the past; and (4) what new developments have the potential to improve crop-weed competition modelling and help address important issues in the future.

2. Why is it useful or important to model crop-weed competition

Following Karplus (1983), Haefner (2005) describes three principal purposes for biological modelling: understanding, prediction, and control, and secondary purposes including providing a conceptual framework, summarising and synthesising information, identifying areas of ignorance, and providing insight. To these we would add the closely related aims of management support, visualisation, communication, education, extension, convincing people, or developing general recommendations or guidelines. All of these apply to crop-weed competition modelling.

Our need to predict the future based on current conditions is perhaps the most obvious reason to model crop-weed competition. In a simple case, we may want a model that can predict the likely yield loss associated with different weed densities in our crop. In reality, this yield loss is likely to depend on many factors besides the density of the weed, such as the weed species and ecotype; the emergence time of the weed cohorts relative to the crop emergence time; soil nutrients; the competitiveness of the species and cultivar of the crop being grown; or the rainfall and temperature experienced in the field over the growing season (Zimdahl, 2004; Patterson, 1995). So instead of the simple model described above, we might want a more sophisticated model that can predict the likely yield loss associated with different weed densities in our crop, while accounting for all these other factors as well.

We also need crop-weed competition models to help inform and guide management decisions, including long-term strategic planning decisions and short-term tactical decisions in response to current conditions (Renton et al., 2015). For example, we may face the tactical decision of whether or not to apply a selective in-crop herbicide, given information about the weed density and the anticipated yield. Or we may face the strategic decision of planning a long-term crop-pasture rotation to best manage weeds while maximising profit. Modelling for management decision support is related to modelling for prediction, but not identical. For example, to help guide the decision of whether or not to apply a selective in-crop herbicide, a model will need to predict the yield-loss likely to occur given the observed weed density, but it will also need to account for the costs and benefits of the different options being considered (Renton and Lawes, 2009; Lawes and Renton, 2010). Applying the herbicide will involve a cost (the time and money involved in application), but also provide a benefit (reduced competition leading to increased crop yield leading to increased income). A good management decision support model needs to predict the outcomes of different management options and also help weigh the costs and benefits of these options. In some cases, accurate predictions may not be necessary, as differences in predictions may not change which option is best overall, or the advantage of switching to the better option may not be practically or economically significant (Renton, 2011a).

Modelling crop-weed competition can also help generate scientific insight and better understanding of the processes and interactions involved. For example, it may be known from empirical data that in certain environmental conditions, a certain weed density in a crop of a certain species sown at a certain density is likely to cause a particular average yield loss, or that a more competitive crop cultivar will reduce weed biomass and seed production by a particular percentage. But it may not be known what underlying processes or mechanisms cause this yield loss. It may be shading and light competition; competition for soil water at various depths in the profile or distances from the cropping row; or competition for different kinds of nutrients. Interactions with insect or fungal pests could also be involved, with the weeds creating conditions that facilitate or interfere with these pests. The processes are likely to vary through space and time. Specific parts of the weed canopy structure may shade specific parts of the crop canopy structure to greater or lesser extent at different points in time through the growing season, or limitations in water and nutrients due to competition may occur at particular depths in the soil profile or distance from the crop row at different times. It is also quite likely that different processes interact over time and space; for example, early competition for water and nutrients may cause an initial reduction in crop growth, which may cause plants to be shorter later in the season, resulting in increased shading by weeds and reduced grain fill.

We also need crop-weed competition models to help communicate, educate and convince people to change their practices or adopt new recommendations based on empirical scientific evidence. For example, there may be evidence that growing a more competitive and expensive crop variety will cause a large reduction in weed seed production, with sufficient long-term impacts on weed seedbanks and future populations to justify its additional expense. But agronomists are reluctant to recommend it because the more immediate benefits to yield are small and long-term benefits are somewhat uncertain and difficult to observe. Or there may be a perception that a certain weed species must be controlled early with an additional herbicide application, while there is some evidence that early competition from this weed species has minimal effect on final yield and controlling the weed with the standard later herbicide application is sufficient. In these situations, well-designed and effectively-used models can help illustrate the empirical or economic evidence in a more convincing way, such as providing a dynamic three-dimensional visualisation of the crop's ability to recover from early competition, or a long-term economic synthesis demonstrating the value of the more expensive cultivar (Pannell et al., 2004; Kragt and Llewellyn, 2014; Lacoste and Powles, 2015).

3. What management options should be investigated?

Models can be used to investigate how management options are likely to impact on crop-weed competition, and interact with other factors such as environment and biological conditions (Zimdahl, 2004). For example, models have been used to investigate the

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