Crop Protection xxx (2016) 1–7

Contents lists available at ScienceDirect

Crop Protection

journal homepage: www.elsevier.com/locate/cropro

Using simulation models to investigate the cumulative effects of sowing rate, sowing date and cultivar choice on weed competition

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ARTICLE INFO

Article history:
Received 9 February 2016
Received in revised form
28 April 2016
Accepted 6 May 2016
Available online xxx

Keywords:
Competition
Cultural weed control
INTERCOM
Suppression
Tolerance

ABSTRACT

With the increasing pressure on crop production from the evolution of herbicide resistance, farmers are increasingly adopting Integrated Weed Management (IWM) strategies to augment their weed control. These include measures to increase the competitiveness of the crop canopy such as increased sowing rate and the use of more competitive cultivars. While there are data on the relative impact of these non-chemical weed control methods assessed in isolation, there is uncertainty about their combined contribution, which may be hindering their adoption. In this article, the INTERCOM simulation model of crop/weed competition was used to examine the combined impact of crop density, sowing date and cultivar choice on the outcomes of competition between wheat (*Triticum aestivum*) and *Alopecurus myosuroides*. *Alopecurus myosuroides* is a problematic weed of cereal crops in North-Western Europe and the primary target for IWM in the UK because it has evolved resistance to a range of herbicides. The model was parameterised for two cultivars with contrasting competitive ability, and simulations run across 10 years at different crop densities and two sowing dates. The results suggest that sowing date, sowing density and cultivar choice largely work in a complementary fashion, allowing enhanced competitive ability against weeds when used in combination. However, the relative benefit of choosing a more competitive cultivar decreases at later sowing dates and higher crop densities. Modeling approaches could be further employed to examine the effectiveness of IWM, reducing the need for more expensive and cumbersome long-term *in situ* experimentation.

1. Introduction

In agricultural systems, a careful balance is required between producing a high value crop yield and minimising costs. In this regard, weeds are the most serious potential threat to maintaining profitable farming systems, responsible for inflicting approximately 34% potential yield loss globally (Oerke, 2006). The introduction of herbicides in the 1960s allowed effective and relatively cheap control of weed species. Unfortunately, over-reliance on herbicides has led to widespread resistance in many problematic weed species (Heap, 1997; Moss et al., 2011) and the current herbicide-based weed control paradigm is widely considered to be unsustainable. In response, an approach which combines herbicides with a range of non-chemical (or 'cultural') weed management options, termed Integrated Weed Management (IWM), is increasingly being employed to compensate for loss of herbicide efficacy (Bond and Grundy, 2001; Lutman et al., 2013; Andrew et al., 2015).

Non-chemical control techniques employed in IWM are numerous and can be divided into those implemented over several seasons, including rotational ploughing and increased crop diversity, and within-season measures. The latter include increased sowing rate and growing more competitive cultivars to minimise weed seed return. Within-season options, that aim to shift the competitive balance in favour of the crop, are the focus of this paper. In most systems, non-chemical weed management options will be employed in combination with herbicides but by increasing crop competitiveness, the required efficacy and reliance on herbicide control is reduced. In the UK, non-chemical techniques are increasingly being utilised to enhance control of the weed species *Alopecurus myosuroides* Huds. in winter wheat (*Triticum aestivum* L). This annual grass species can cause substantial losses to wheat (Storkey et al., 2003) and herbicide resistance is widespread in North-West Europe (Moss et al., 2011; Lutman et al., 2013; Keshtkar

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http://dx.doi.org/10.1016/j.cropro.2016.05.002
0261-2194/

Please cite this article in press as: Andrew, I.K.S., Storkey, J., Using simulation models to investigate the cumulative effects of sowing rate, sowing date and cultivar choice on weed competition, Crop Protection (2016), http://dx.doi.org/10.1016/j.cropro.2016.05.002

et al., 2015), and is the focus of this study.

Non-chemical control tools require financial or temporal investments and their effectiveness varies from year to year. The resulting uncertainty means non-chemical control strategies tend only to be utilised when herbicides begin to fail (Bastiaans et al., 2008), as is currently the case for the control of *A. myosuroides* in the UK. Recommended non-chemical control options for *A. myosuroides* in the UK include rotational ploughing, use of spring crops (*A. myosuroides* mainly germinates in the autumn), delayed sowing date (to allow the use of a stale seedbed), increased crop sowing rate and the use of more competitive crop cultivars (Lutman et al., 2013).

Non-chemical control techniques are infrequently studied in combination, owing to the scale of experiment required, and data are therefore lacking on whether combined effects are additive, synergistic or antagonistic. Weed control measures have previously been examined with the use of simulation models. Models allow a means of studying scenarios *in silico*, providing insight without the need for large-scale experimentation. One well developed and validated model of crop/weed competition is INTERCOM, initially developed by Kropff and Spitters (1992) which has been parameterised for several crop and weed species since its inception (van Ittersum et al., 2003). When tested using sugar beet and *Chenopodium album* L., the original model explained 98% of the variation in yield loss (Kropff et al., 1992) and since then has been adapted to model competition from a range of weed species, including *A. myosuroides* in winter wheat under UK conditions (Storkey and Cussans, 2007). The model includes a range of eco-physiological parameters that determine the competitive balance between crops and different weed species and is weather driven allowing variability in output owing to environmental stochasticity to be quantified. The model can be used to examine the impact of sowing density, sowing date and crop cultivar on the outcome of crop/weed competition.

In this paper, we demonstrate how the INTERCOM model of plant competition can be utilised to observe the combined effect of sowing density, sowing date and cultivar choice, using wheat and *A. myosuroides* as model species. Furthermore, we discuss the advantages and disadvantages in employing models to understanding weed control initiatives and advising on their future use to support the implementation of IWM.

2. Materials and methods

2.1. Description of the INTERCOM model

The INTERCOM model makes predictions of the outcomes of competition between a crop and a weed based on leaf area production and distribution through the canopy in daily time steps (Kropff and van Laar, 1993). The primary driving environmental variables are photoperiod, temperature and available water. Temperature and water are growth-limiting, whilst accumulated photoperiod and thermal time mediate switches between developmental stages. The model has three discrete periods. Before plants begin competing for resources, growth is sink limited and modelled using an exponential relationship with biological time. In the original model, thermal time was used but, in later versions, a variable incorporating incident radiation (effective day degrees) was found to better capture differences between the growth of autumn and spring emerging cohorts (Storkey, 2004). A total green area index (GAI) of 0.75 is used as a switch between sink and source limiting growth − the next phase of the model. The ability of crop and weed to intercept light is determined through their share of the canopy (leaf area index), leaf traits related to light absorption (such as specific leaf area) and the vertical distribution of leaf area through the canopy. The model also accounts for changes in leaf traits and light absorption over time (Storkey, 2005). Plant height growth is predicted to follow the logistic function against accumulated photothermal time, as defined by Spitters (1989). Precipitation data and soil water balance functions are included in the model, using calculated rates of transpiration and evaporation. Water becomes limiting when soil moisture falls below a predetermined level, and the relationship between the potential growth rate and water limited growth determined from an empirically derived relationship The final phase of the model is senescence and, for wheat, grain filling. Re-allocation of resource from stems and leaves to grain is modelled using functions from the Sirius model of wheat growth (Jamieson et al., 1998).

The version of INTERCOM utilised in this study has been parameterised for winter-sown wheat and *A. myosuroides* for improved description of winter wheat growth and partitioning (see Storkey and Cussans, 2007, where a detailed description of the model can be found). It was amended for the purposes of this study in C++ as described below.

2.2. Parameterising INTERCOM for wheat cultivars

In the winter wheat/*A. myosuroides* model, wheat was originally parameterised using data from the cultivar Consort (Storkey and Cussans, 2007). However, it has been frequently demonstrated that wheat cultivars differ in their ability to compete against weeds. While INTERCOM has been used in the past to inform the breeding of competitive rice cultivars (Bastiaans et al., 1997), here, we take the novel approach of using the model to quantify the relative impact of cultivar choice on weed competition in the context of variable sowing rate and sowing date. The variability in cultivar competitive ability has been attributed to numerous plant traits, including height, leaf area and developmental speed (Andrew et al., 2015). Many of these are traits utilised by INTERCOM to make predictions of competitive outcomes.

The model was parameterised for two contrasting wheat cultivars, Duxford and KWS Santiago. These cultivars were selected based on three years of study (2012, 2013, 2014) in outdoors containers, where they represented the extremes in terms of competitiveness when compared to a range of ten modern wheat cultivars. Duxford was frequently reported as the strongest suppressor of *A. myosuroides* across three years of study, whilst KWS Santiago was frequently the poorest performer (Andrew, 2016). Using data collected from a series of outdoor, container-based experiments based at Rothamsted Research, UK, data were available to parameterise the model for different cultivars. To parameterise seedling growth rate, the protocol used in Storkey (2004) was followed; sequentially sampling seedlings over a two month period. For parameters determining resource competition, the cultivars were grown in competition with *A. myosuroides* in outdoor containers (40 × 32 cm) in a fully replicated experimental design repeated over three years and a range of morphological traits measured through the season. A selection of the original model parameters for wheat (cv. Consort) and for the two contrasting cultivars can be found in Table 1. The model was separately parameterised for each cultivar in C++. The main differences between the cultivars were in their rate of development, early height and early vigour (Fig. 1). Duxford tended to have a relatively erect canopy structure early on and a high seedling growth rate (related to a higher specific leaf area and lower partitioning to roots) whereas KWS Santiago tended to delay shoot extension and be relatively prostrate in the seedling stage.