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Integrating pest population models with biophysical crop models to better represent the farming system☆

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ABSTRACT

Farming systems frameworks such as the Agricultural Production Systems simulator (APSIM) represent fluxes through the soil, plant and atmosphere of the system well, but do not generally consider the biotic constraints that function within the system. We designed a method that allowed population models built in DYMEX to interact with APSIM. The simulator engine component of the DYMEX population-modelling platform was wrapped within an APSIM module allowing it to get and set variable values in other APSIM models running in the simulation. A rust model developed in DYMEX is used to demonstrate how the developing rust population reduces the crop's green leaf area. The success of the linking process is seen in the interaction of the two models and how changes in rust population on the crop's leaves feedback to the APSIM crop modifying the growth and development of the crop's leaf area. This linking of population models to simulate pest populations and biophysical models to simulate crop growth and development increases the complexity of the simulation, but provides a tool to investigate biotic constraints within farming systems and further moves APSIM towards being an agro-ecological framework.

1. Introduction

Crop simulation modelling has progressed from specific crop or soil models, to linked crop and soil models, to the farming systems models that are common today (Moore et al., in this issue). This paper uses developments in the Agricultural Production Systems simulator (APSIM) (Holzworth et al., 2014; Keating et al., 2003) to present a case for linking a population modelling framework to a farming systems modelling framework. The combination enables the interaction of biotic constraints and the cropping system to be studied. However, this increased capability also increases complexity.

Farming systems models like APSIM, are better described as frameworks, because their software development allows the interconnection of the biophysical and management models to simulate processes within the farming system (Holzworth et al., 2010). Many of the new developments within the APSIM framework have been facilitated by the adoption of a Common Modelling Protocol (CMP) (Moore et al., 2007) that has simplified the integration of components from other modelling tools. This work has enabled APSIM, a predominantly cropping model, to be combined with more complex grazing, pasture (Moore et al., 1997) and animal models (Freer et al., 1997) to more accurately represent the typical enterprises within a farming system (Holzworth et al., 2014). The linking of animal models to crop and pasture models was the initial step in accounting for the resource competition between different organisms within an APSIM simulation.

Simulating farming systems with APSIM has been of great benefit to agricultural production in Australia (Carberry et al., 2009a; Hochman et al., 2009) and in developing countries (Komarek et al., 2012; Lisson et al., 2010) as it has encouraged new developments, APSIM-ORYZA (Gaydon et al., 2012a, 2012b), APSIM-Oil Palm (Huth et al., 2014), and partnerships (Rosenzweig et al., 2013) that require the development of new capacity.

A success of APSIM is how it has helped researchers, farmers and consultants learn about their system (Carberry et al., 2009b) and more importantly identify how managing farm resources can improve production and profit (Murray-Prior et al., 2005). An increased understanding of the farming system has evoked new questions, which in turn, initiated further development within

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APSIM. The importance of stored soil water in rain-fed farming systems stimulated studies into the cost of lost grain by poor weed control in summer fallows (Hunt and Kirkegaard, 2011) and via the intercropping module (Carberry et al., 1996) competition between crops. A result has been the development of specific weed modules and competition studies (Deen et al., 2003; Robertson et al., 2001). The development of seed bank population models extended this work to investigations of the relationship between management and crop growth on the weed population. Initially, the seed bank models were constructed within APSIM's manager language (Grenz et al., 2006) but as the problem space became more complex alternatives were investigated.

A second seed bank model was developed in the visual modelling framework Vensim™ and linked to APSIM to evaluate farm management strategies to reduce weed seed banks (Smith et al., 2005). The Vensim-APSIM seed bank model was successfully used to investigate weed resistance in Australian rain-fed farming systems (Thornby and Walker, 2009; Thornby et al., 2010). However, the underlying structure of the Vensim™ seed bank model constrained this research, because of restrictions on the number of cohorts available, preventing it from modelling all the possible weed cohorts with their different genetic heritage positioned at different layers within the soil.

A conclusion from these studies was that when trying to combine agro-ecological models with population models a degree of compromise was required, either on the side of the agro-ecological model or the population model.

DYMEX (Sutherst and Maywald, 1998) is a detailed climate-driven, process-based, population cohort modelling framework. DYMEX has been used to model biotic constrains within agro-ecosystems, specifically insects (Yonow et al., 2004), diseases (Lanoiselet et al., 2002; White et al., 2004) and weed populations. A union between DYMEX and APSIM would provide a method to efficiently and generically integrate population models within the APSIM framework, reduce the current compromises (limited cohorts) and so make a further step in the transition of APSIM from a cropping systems to an agro-ecological model.

This paper will briefly summarise the key features of APSIM and DYMEX, describe how the generic communications framework underpinning APSIM has been used to couple the two models (Holzworth et al., 2010) and to demonstrate the application of this coupled model using interactions between stripe rust (*Puccinia striiformis* Westend) and wheat as a case study. The case study will highlight the aim of the DYMEX–APSIM link and how it can be used to model the affect of an increasing pest population (rust) on the growth and development of the crop (reduced leaf area).

2. Linking a generic population model to a generic agro-ecological model

2.1. The Agricultural Production System Simulator (APSIM)

The APSIM framework enables biophysical and management models to connect and interact. The success of these connections is a result of the development of the CMP that APSIM uses as the communications infrastructure, that allows models constructed in different software languages to communicate (Holzworth et al., 2010). For a more detailed description of APSIM its function, design and the models available see Holzworth et al. (2014) and the earlier paper of Keating et al. (2003).

2.2. DYMEX

DYMEX is a software package for building and running multi-cohort population models. Its original objective was to enable the building of mechanistic, process-based population models without the need for computer programing expertise (Sutherst et al., 2000). The package is divided into two parts, the model builder and the simulator. The builder allows the construction of the model from individual component modules, processes, and functions. The central component of a DYMEX model is the "lifecycle", which is composed of life stages though which each individual passes during its life (Maywald et al., 2007). All other modules and components exist to support the lifecycle. The builder itself uses a visual construction approach and libraries of pre-built modules and functions to simplify model construction.

The simulator is the second half of the DYMEX package. It allows models constructed in the builder to be processed. The simulator has two roles, firstly an engine that executes models that have been constructed in the builder, and secondly, a graphical user interface that allows parameters to be adjusted and outputs to be reported as graphs and tables.

2.3. DYMEX–APSIM link

To create a link between DYMEX and APSIM, the DYMEX simulation engine was incorporated into APSIM. This technically integrated approach (Knapen et al., 2013) was chosen over the alternatives (incorporating an APSIM simulation into the DYMEX simulator or writing a separate piece of linking software) for two reasons: firstly, this approach enables multi-point models (the ability to simultaneously simulate multiple points in space and the interactions between them, thus allowing the simulation of weed patch dynamics or disease movement between points) that link agro-ecological and population sub-models and secondly, the input and output facilities in APSIM are more suited to running and interpreting detailed biophysical models. A software interface to the DYMEX simulation engine (without its graphical user interface) was developed to implement DYMEX as a CMP-compliant component (Moore et al., 2007). Because APSIM simulations use the CMP, the DYMEX component executes with the rest of the APSIM simulation, it accepts information from other modules in the simulation (e.g. weather data drawn from standard APSIM climate files) and sends information (e.g. rust lesion growth) to other models (Fig. 1). The component interface was written to allow any model constructed with the DYMEX builder to be linked into APSIM.

Because DYMEX conceives of a population of organisms as a series of cohorts each of which can be in different life stages, the data structures used in DYMEX are complex. In the case study below, this information needed to be "unpacked" and transferred to the APSIM-Plant component, which deals in simpler data types. As a temporary measure, the APSIM-Plant component (the crop model in APSIM) was left unmodified and a script was written in the GRAZPLAN management component referred to as the CPI manager (the manager language used in the GRAZPLAN modelling framework) (Moore et al., in this issue) to perform the translation task.

Converting an existing DYMEX model to run in APSIM or to create an APSIM-enabled model from scratch requires three steps. Firstly, a DYMEX model is built in the DYMEX builder and the variables being shared with APSIM are defined. Secondly, the model is tested in the DYMEX simulator. Thirdly, the DYMEX–APSIM component is included within an APSIM simulation and directed to use the DYMEX text file created by the DYMEX builder. The variables being exchanged between APSIM and DYMEX are defined in the CPI management component so they can be queried or set at the correct time during a daily simulation cycle. Once connected, the DYMEX–APSIM component will display and allow modification of all writeable DYMEX variables. Further development of the DYMEX model can occur in the DYMEX builder and this will be