Insect-pathogen-crop dynamics and their importance to plant biosecurity under future climates: Barley yellow dwarf virus and wheat – a case study

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Abstract

Predicted climate change in Australia points to elevated atmospheric CO_2 concentration, increased temperatures and lower and more variable rainfall across much of southern Australia. There are few crop models that have integrated pest and disease epidemiology modules that allow the exploration of the interactions with environmental factors, let alone the spatial behaviour across regions. Such models, however, are needed to develop robust biosecurity adaptation and mitigation strategies. We are studying wheat (*Triticum astevium*) and the bird cherry-oat aphid (*Rhopalosiphum padi*) that vectors Barley yellow dwarf virus (BYDV), an economically important cereal disease as a case study. In this study we are developing a spatially explicit model that couples aphid dispersal, host-plant physiology, virus and vector population dynamics and projected climate change conditions to predict the individual species responses and shifts to geographic ranges, and impact on wheat yield production. Model functions are supported by empirical data of the influence of the presence of BYDV infected plants on aphid feeding behaviour, virus acquisition and transmission rates and host-plant physiology using both growth chambers and the Australian Grains Free Air Carbon Dioxide Enrichment (AGFACE) facility. This paper reports on the development progress of the integrated modelling and experimental approach to understand the possible effects of climate change on wheat yield in Australia using an aphid-BYDV-wheat modelling system.

Key words

R. padi, BYDV, climate change, pest, simulation model

Introduction

Climate change is being observed worldwide, and with increased incidence of extreme weather events poses considerable threat to the security of the global food supply (Chen and Kates 1994). For Australia, with an arid environment, these risks could have ramifications on market access and terms of trade. In Victoria, small grain production is an important contributor to the economy with an annual farm gate value of $1200 million (Brown et al., 2007).

The development of climate based niche forecasting models e.g. Climex (Sutherst and Maywald, 1985) have assisted with the prediction of insect species distributions, for example, the poleward movement of pests, and underpinning pest mitigation strategies in response to changes in global warming (Morgan 2000). However, compared with the prediction of changes in species distribution, the prediction of pest population dynamics in response to climate change is more challenging, as it requires consideration of both host and pest dynamics (Bale et al., 2002) and little empirical knowledge is available demonstrating how climatic variables influence the biological interrelationships between pests and pathogens in crop production systems (Chakraborty et al., 2008; Diffenbaugh et al., 2008). Furthermore, few crop models have integrated pest and disease epidemiology sub-models and there is increasing acknowledgment that there is a need to take a more holistic approach to modelling to allow for the projection of the impact of pests and pathogens on crop production under future climates (Chakraborty et al., 2008).

In this paper we report on the progress of an integrated modelling and experimental approach that will allow for impact assessments of pests and diseases at both the spatial and temporal scales. We use the aphid transmitted plant pathogenic virus, barley yellow dwarf virus (BYDV), an economically important cereal disease as our model system.

Aphid-BYDV-Wheat model development

The modular modelling software Stella (iseesyetems) and Dymex (Hearne Scientific Software) are being used to construct a spatially explicit model coupling vector population dynamics and dispersal, pathogen movement and host-plant physiology (Figure 1). The biophysical processes in the model are driven by the climatic inputs of daily rainfall, minimum and maximum temperature, solar radiation, humidity and wind run, and with reference evapotranspiration (ref ET) computed using the modified Penman-Monteith equation as given by the FAO. The crop model is a simplification of the transpiration driven wheat model of O'Leary and Connor (1996) with additional CO_2 functions added from CropSyst (Stockle et al., 2003). The model runs on a daily time step with 3 core sub-modules.

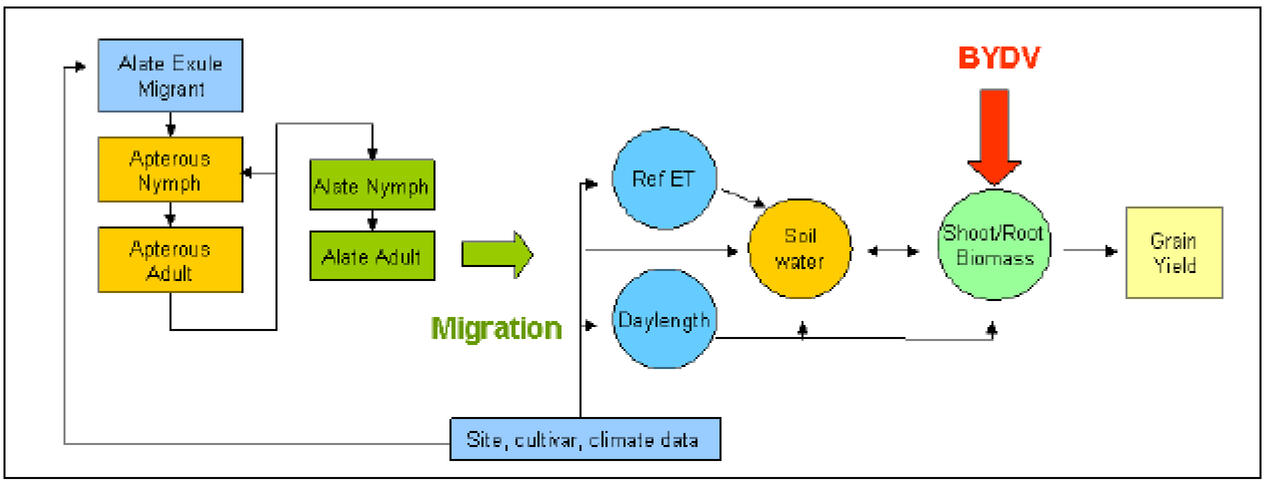

Figure 1. Schematic representation of the coupled sub-models

The phenology sub-module predicts phase duration in response to daily fluctuations of temperature and daylength for the key stages of germination, stem elongation, booting, anthesis and maturity as a function of thermal and photothermal time.

The soil water balance sub-module is structured around a single-layer design to minimise complexity. Transpiration from the crop is influenced by water availability and reduced when relative available water falls below 0.3. Evaporation from the soil surface was defined as the classic 2-stage process following Ritchie (1972) whereby the supply of energy drives the actual evaporation during stage I and the supply of water primarily limits evaporation during stage II. Drainage in the model is computed using a simple bucket-tipping concept.

The biomass-yield model computes the daily increment in biomass as a function of transpiration and transpiration efficiency, which itself is a function of radiation use efficiency (RUE) following O'Leary and Connor (1996). A temperature growth limiting factor was applied to RUE. In our model the soil mineral nitrogen pool is presently non-limiting and no nutrient limiting factor on RUE is applied. Biomass is partitioned between root and shoot, and following anthesis into the grain during grain filling. The daily increment in biomass decreases linearly with corresponding increases in root and shoot senescence until maturity. The maximum size of the sink pool at anthesis (proportion of stem reserves that contribute to grain yield) is an input that can be modified by the user to adjust for environmental conditions.

The baseline relationship for the impact of BYDV on the host plant has been calculated using relationships from Thackray et al. (2009). The key assumption was that yield is most adversely affected in the first 8-9 weeks post-sowing i.e. before stem elongation. BYDV was applied as a stress factor (ranging from 4 to 60%) on the daily biomass increment, impacting on the green leaf available for photosynthesis. Further impacts on host-plant physiology (e.g. amended root:shoot partitioning) are currently being incorporated into the model.

The aphid population sub-model initiates the over-wintering population on perennial ryegrass/irrigated pastures (green bridge). The model is constructed around the aphid life cycle of apterous nymphs and adults, with alate nymphs and adults produced under conditions of over-crowding. High temperatures sustained over a number of days during summer results in high mortality rates and reduced population size of *R. padi*. Alate adults are a winged form and when environmental conditions are favourable (e.g. daylength, autumn rainfall) these aphids migrate on prevailing winds into wheat fields where they colonise and disperse. The timing of aphid migration to the crop is a critical determinant of crop production. If the colonising aphids carry BYDV, there is a latency period of 18 days following arrival before the BYDV stressor triggers reduced daily growth rates in the infected plants (cells) in the model. The coupling of the aphid and wheat sub-models in the Dymex modelling environment will allow for automatic parallel computation of aphid and wheat plant cohorts, each with individual characteristics for aphid fecundity or level of BYDV induced stress on daily crop growth. The integration of the aphid and wheat sub-models across space will require the development of spatialised modelling capability within Dymex, and this is currently under construction. Furthermore, this will enable the relationship between migration day and impact on above ground biomass production to be modelled over time, and project subsequent impacts from aphid dispersal on crop disease and severity of associated yield reduction.

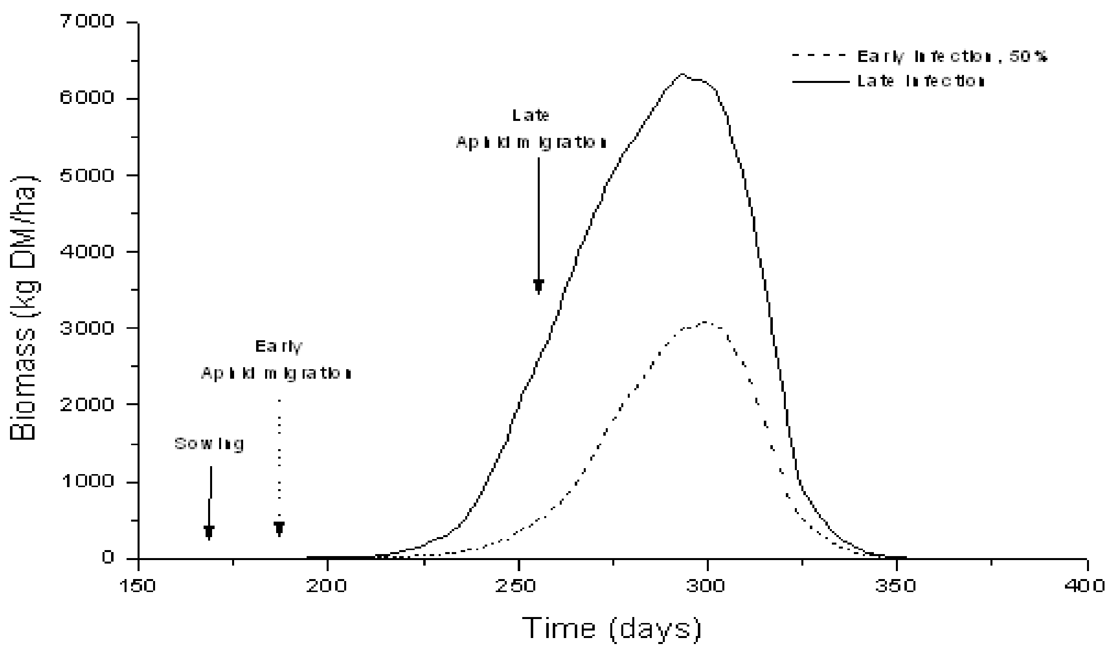

Figure 2. Conceptual biomass reduction of wheat as a function of aphid migration and sowing date, and level of BYDV infection.

The considerable variation in the literature around potential yield reduction from BYDV infection arises from many sources including the variation in aphid migration date, the magnitude of infection and the timing of when the infection status was assessed. For preliminary assessment a linear relationship between yield loss and the date of BYDV inoculation prior to stem elongation was derived using existing literature from Western Australia and Victoria that showed a yield reduction of between 13-25 kg/ha per % BYDV infection (McKirdy et al., 2002) and 40 kg/ha per % BYDV infection (Smith and Sward 1982), respectively. Furthermore, little knowledge is available on how eCO_2 may modify these relationships, and the ability for the host plant to withstand pathogen loads. These model relationships will be refined as empirical data on plant growth in response to the timing of infection under eCO_2 becomes available.

Performance of the crop model

The crop model in the absence of BYDV stress was validated against the 2007 data from AGFACE with 4 simulations; a factorial of CO_2 (380 and 550ppm), sowing date (days 169 and 235) and water supply (rainfed and irrigated). The comparison between the observed and simulated grain yield provided a Root Mean Square Error of 870 kg/ha that is close to published errors of comparable crop simulation models. In the model's current form the grain yield is under-predicted and it is probable that part of the larger error is an artefact of the simplified soil water balance sub-model which is particularly sensitive to initial soil water conditions. Datasets are being compiled from two regions of Victoria to undertake a calibration function for inclusion in the water sub-module.

Empirical studies

Experimental work providing empirical data to support the model development is being conducted in controlled growth chambers and in the field within the AGFACE facility at Horsham, Victoria. These studies include monitoring aphid migration and populations throughout the crop growing season using yellow sticky traps, water traps and plant assessment across ambient CO_2 (380ppm) and elevated CO_2 (550ppm) rings. There is considerable variation in the transmission efficiency of BYDV (Rochow and Eastop 1966), and to better understand this variation, the feeding behaviour of individual aphids on plants grown under ambient and elevated CO_2 is being assessed using EPG (Electrical Penetration Graph) methodology. EPG data is then correlated with specific feeding behaviours e.g. salivation, probing, sap ingestion and used to estimate duration of acquisition and transmission (Tallingaii 1988) (Figure 3).

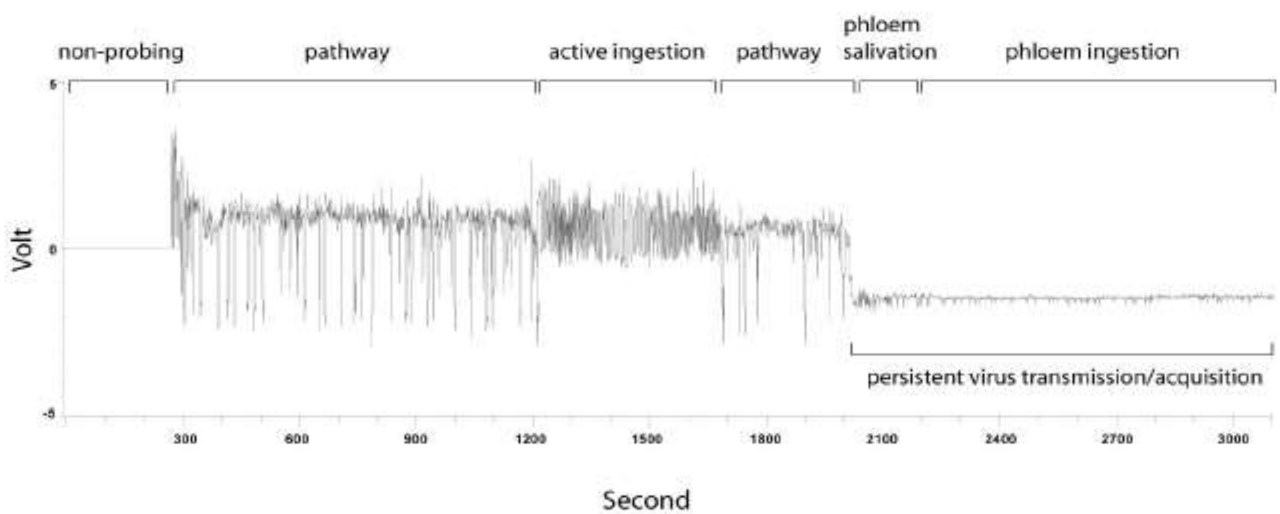

Figure 3. Conceptual EPG setup and identified feeding states

Next steps

The sub-models will be integrated into the Dymex software package to project the spatial impact of BYDV on wheat yield under future climates across the major wheat growing regions of Australia; notably Victoria, South Australia and Western Australia. These projections arising from the development of a holistic pest-pathogen-crop simulation modelling tool will provide capability for government and policy makers to review plant biosecurity policy to minimise any increased risk from BYDV posed by Australia's changing climate.

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