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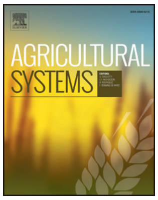

Modelling the impacts of pests and diseases on agricultural systems

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ABSTRACT

The improvement and application of pest and disease models to analyse and predict yield losses including those due to climate change is still a challenge for the scientific community. Applied modelling of crop diseases and pests has mostly targeted the development of support capabilities to schedule scouting or pesticide applications. There is a need for research to both broaden the scope and evaluate the capabilities of pest and disease models. Key research questions not only involve the assessment of the potential effects of climate change on known pathosystems, but also on new pathogens which could alter the (still incompletely documented) impacts of pests and diseases on agricultural systems. Yield loss data collected in various current environments may no longer represent a adequate reference to develop tactical, decision-oriented, models for plant diseases and pests and their impacts, because of the ongoing changes in climate patterns. Process-based agricultural simulation modelling, on the other hand, appears to represent a viable methodology to estimate the impacts of these potential effects. A new generation of tools based on state-of-the-art knowledge and technologies is needed to allow systems analysis including key processes and their dynamics over appropriate suitable range of environmental variables. This paper offers a brief overview of the current state of development in coupling pest and disease models to crop models, and discusses technical and scientific challenges. We propose a five-stage roadmap to improve the simulation of the impacts caused by plant diseases and pests; i) improve the quality and availability of data for model inputs ; ii) improve the quality and availability of data for model evaluation; iii) improve the integration with crop models; iv) improve the processes for model evaluation; and v) develop a community of plant pest and disease modelers.

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1. Introduction

Quantifying the impacts of plant pests and diseases on crop performances represents one of the most important research questions for agricultural simulation modelling (Newman et al., 2003; Savary et al., 2006; Esker et al., 2012; Whish et al., 2015a). In the past, theoretical frameworks were thus developed to take into account the impact of pests and disease on yield as separated by the other limiting factors due to genotype x environment x management interactions. De Wit and Penning de Vries (1982) introduced the concept of production situation, which encompasses the combination of yield defining and yield limiting factors, therefore determining the attainable yield. A production situation also includes farmer crop management including pest and disease management. This widely accepted categorization of yield levels incorporates the crop genetics among the factors defining potential yield, and groups the water and nitrogen stress as limiting factors to attainable yield. Later, Rabbinge (1993) defined (1) a potential yield, defined by solar radiation and temperature, (2), the attainable yield, limited by water and nutrient availability, and (3) the actual yield, reduced by diseases, pests, and environmental stressors. According to this framework, reduction of crop yield due to biotic stresses corresponds to the difference between the attainable and actual yield.

The classification of yield levels constitutes the basis to guide strategic decisions in the development and application of cropping system models (e.g., Jagtap et al., 1999; Cheeroo-Nayamuth et al., 2000; Abeledo et al., 2008), including the quantification and modelling of yield losses (Zadoks and Schein, 1979; Savary et al., 2006; Esker et al., 2012). For instance, a common procedure in the calibration of cropping system models is to simulate the attainable yield, that is, the yield of an uninjured (disease and pest free) crop. These models are parameterized by comparing model outputs with reference data collected in experimental trials where there is little or no biophysical stress, so that yields are close to potential production. This reduces the impact of experimental noise on the parameters representing the crop morpho-physiological traits (Wolf and de Wit, 2010; Djabi et al., 2013; Bregaglio et al., 2015). Also, most of the available crop system models offer options that enable

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the user decide to activate nutrients and water limitation, with a default configuration running the potential production level (e.g., WOFOST, Supit et al., 1994, Boogaard et al., 2011,; DSSAT, Jones et al., 2003, CropSyst, Stöckle et al., 2003; AquaCrop, Raes et al., 2009). Currently, such a "pest and disease switch" is still missing in many crop models, although developments in the last decades are moving towards the quantitative description of the impact of pest and diseases on yield.

Plant pathogens and crop-feeding insects are integral part of agroecosystems, where they have coevolved with crops over millennia (McCann et al., 2013). A cascade of mutual and complex interactions exists between the cultivated crops and their pests and diseases (Berger et al., 2007). Two main groups of processes may be considered to address these systems, corresponding to scientific domains where modelling, in very diverse forms, has developed. A first group is related to pathogen population dynamics, and concerns the dynamics of Pests and Disease Models (PDM), through which populations may spatially expand and temporally increase. The second group addresses crop losses, and focuses on the consequences of the host-pathogen interactions on crop physiological processes and yield. These two broad groups of processes are strongly responsive to physical, biological, social, and economic factors where crops are cultivated (Zadoks and Schein, 1979). These two scientific domains were recently discussed by Cunniffe et al. (2015), who identified the linking of epidemiological models to yield and ecosystem services as the first challenge in modelling plant disease, stating that models should incorporate sufficient *epidemiological realism* in order to analyse and predict the *effects of disease and host dynamics on yield*.

Additional key research questions involve the assessment of the potential effects of climate change (Rosenzweig et al., 2001), of technology shifts (Beddington, 2010), and of biological invasions (Venette et al., 2010) on the future impacts of pests and diseases on agricultural systems.

In part because crop pests and diseases are inherently part of cultivated systems, the measurement of their impact on crop performances is a field of its own (e.g., Madden, 1983; Campbell and Neher, 1994; Brown and Keane, 1997; Savary et al., 2006). Only some overall estimates are available, among which is the often cited ranges produced by Oerke (2006). Esker et al. (2012) provide a recent review of the current scientific framework to assess the importance of pests and diseases to crop production, including consideration (i) of production situations and associated (uninjured) attainable crop yields, (ii) of the effects of yield-limiting factors (i.e., abiotic stresses) on the harmful effects of pests and diseases, and (iii) of the interactions among pests and diseases. These three elements have been analysed in a few important crop-pest systems, such as in potato in the USA (Johnson, 1992), groundnut in West Africa (Savary et al., 1990; Savary and Zadoks, 1992), lowland rice in tropical Asia (Savary et al., 2000a, b), and wheat in Western Europe (Willocquet et al., 2008). These examples indicate that (1) the impact of pests and diseases may strongly depend on production situations and on the associated attainable yields; (2) ignoring the interaction of pests and diseases may lead to substantially incorrect estimates of their impact on agricultural production.

The improvement and application of PDM for predicting yield losses to reduce risks to global food security and adaptation to climate change is still a challenge for the scientific community (e.g., Garrett et al., 2006; Savary et al., 2011). Data collected in various environments no longer represents a reference data set for the development of empirical models, because the climatic patterns the models were calibrated for are changing. Because it enables addressing 'what if' questions on the basis of quantitatively known processes, simulation modelling represents a central approach to estimating the impact of the potential effects of climate change on agricultural production.

The objective of this paper is to present an analysis of the technical and scientific challenges in the development of process-based models for pest and disease modelling, and a possible road map to improve their capability for estimating impacts on agricultural production.

2. New challenges and goals

Applied modelling of crop diseases and pests has been dominated by short term, tactical questions, such as the development of support capabilities to schedule scouting or pesticide applications, i.e., decision support systems (DSSs; e.g. Welch et al., 1978; Magarey et al., 2002, Isard et al., 2015). These modelling activities are often based on specific pest-crop systems, in specific environments, and based on multi seasonal observations, that allowed the building of robust empirical relationships using weather variables and crop phenology (Madden et al., 2007). Working on given, local patterns of weather variation and on specific pathogen and pest species has simplified the representation of the interactions between a biotic stressor and a host. Key aspects in the development of DSSs include knowledge on system dynamics, built on data from multiple seasons and collected in the pest-crop systems of interest (Madden et al., 2007). An alternative approach has been to build models parameterized from independent, controlled experiments, targeted at identifying organisms responses to a range of environmental factors. Two of the most popular examples are phenology models for insect pests (Welch et al., 1978) and SEIR (Susceptible-Exposed-Infectious-Removed) and infection models for plant pathogens (Zadoks, 1971; Magarey et al., 2005). These kinds of models could have application for determining how the changing climate might also alter the frequency of pesticide applications. In some cases, it may be possible to estimate yield impacts by converting forecasts of pest or disease intensity to projections of yield loss (Dillehay et al., 2005).

New challenges and goals are rerouting or integrating the priorities of pest and disease modelling. The main challenge is due to climate, which has now been demonstrated to change temperature averages, as well as rainfall means and distributions in the season, and to increase their variability. The shift to a non-stationary climate now implies that observed datasets are no longer a sufficient base to predict system behaviour even at specific locations where the data were collected. There is evidence that pathogens which for decades have had no impact on crops in specific environments are now becoming key determinants of crop yield (e.g., Lees and Hilton, 2003; Yang and Navi, 2005; Berger et al., 2007; Parker and Warmund, 2011; Gramaje et al., 2016). At the same time, the increasingly comprehensive goal of estimating risks to global food security requires the inclusion of geographical areas and production system where the available baseline data are not adequate to develop local, robust empirical relationships. Changes in weather patterns make it impossible to address these questions solely via field experiments. Empirical approaches, based on, e.g., statistical models, could rapidly bring about issues associated with non-linearity of responses of processes (Garrett et al., 2006) and for climatic conditions which are beyond the ranges in which models are developed. Also, the goal of making estimates of pest and diseases dynamics under future conditions precludes trend analysis, which would be built on the evidence collected from different weather patterns. Process-based modelling, combined with the careful design of scenarios to analyse impacts, provides an avenue to address these questions. Shared modelling structures among a network of scientists from different fields appear to be a most appealing and efficient way to scientifically address these challenges.

In addition, applications of pest and disease modelling are becoming increasingly important for strategic decisions, such as breeding for host plant resistance in future climate scenarios (e.g., Duveiller et al., 2012), policy-making and priority-setting for research (e.g., Willocquet et al., 2004), applications for risk analysis of alien invasive species (Venette et al., 2010), and for resource allocation (Beddow et al., 2015). A new generation of tools based on state of the art knowledge and technology is needed to allow system analysis including key processes and their dynamics over an appropriate range of environmental variables.

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