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An integrated and modular model for simulating and evaluating how canopy architecture can help reduce fungicide applications

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Highlights: An integrated model coupling architectural canopy development, disease dynamics, pesticide application, pesticide decay and effect of pesticide on disease dynamics has been developed. It allows simulation of the dynamics of epidemics overall a growth season, together with the evaluation of impacts on environment, yield reduction and erosion of pesticide efficiency. This tool allows for a multi-criteria evaluation of different fungicide applications strategies and for designing new strategies that reduce pesticide applications by increasing natural resistance linked to canopy architecture.

Keywords: Pesticide, architecture, simulation, disease escape, Septoria, Wheat.

INTRODUCTION

European countries are moving towards the promotion of a sustainable agriculture that balances production and profitability with product quality and environmental protection. To reduce the use of chemical protection, it is possible to optimize fungicide applications, use resistant or tolerant varieties and improve the control of pests by an appropriate management of the dynamic of crop canopy architecture.

The canopy architecture determines the life environment of the pathogen: it is responsible for the amount and location of its substrate (healthy leaf surfaces), and for the distances to travel to colonize healthy tissues from infected areas. Focusing on wheat, a number of studies showed that canopy architecture significantly modulates Septoria epidemics (Eyal, 1971, Bahat et al. , 1980, Lovell et al. 1997 and 2004, Shaw and Royle, 1993), and that it is a relevant target for improving disease escape (Lovell et al., 2004; Ando et al. 2005) . Such effects however vary with climatic condition and are not easy to disentangle experimentally. The recent developments of models that couple a 3D model of the development of architecture and epidemics (Calonnec et al. 2008, Robert et al. 2008,Pangga et al., 2011) makes it possible to better understand the conditions of success of such strategies.

The canopy architecture also influences the interception of the fungicide and its distribution on the plants. This directly determines the fraction of pesticide that actually reaches pathogens, therefore the efficacy of the treatment. When spraying, the pesticide interception by the canopy and the fraction reaching the ground are often estimated empirically or by an expert judgment, although it is possible to asses it by modeling when canopy architecture is known.

Finally, the architecture determines the microclimatic conditions on leaves, and thus the environmental fate of the applied products. The environmental fate of a fungicide depends on its ability to penetrate the plant to degrade, to volatilize to the atmosphere or to be washed-off by rain (Willis et al., 1987). Volatilization from the canopy may represent more than 10% of the applied dose in a few days or weeks depending on the physicochemical nature of the compound, application method, surface properties and climatic conditions (van den Berg et al., 1999). Leaching by rain is a potentially significant source of dissemination of pesticides to soil and water. Its importance depends on the pesticide, the time between treatments, the intensity and duration of rainfall (Aubertot et al. 2005). Photodegradation also involves radiative transfer to the leaf surface (Katagi, 2004). Models recommended for the pesticide registration on national or EU levels, such as PEARL (Leistra et al., 2001) describe this overall behavior but still face the limits of knowledge about certain processes taking place on the foliage (Scholtz et al., 2002; Leistra et al., 2005) and of simplifications in the representation of canopy architecture.

An integrated assessment of the sustainability of a pesticide reduction strategy must also take into account the erosion of efficacy of chemicals.

The objective of this work is to build an integrated model for simulating the effects of architecture on the dynamics of the epidemics, its interactions with pesticide interception and consequences on the efficacy and the environmental fate of the products. The ultimate goal is to optimize the strategies of fungicide application and to use disease escape linked to architecture in order to reduce the amounts of applied fungicides. In this perspective, we also aimed at providing post-processing utilities for a multi-criteria evaluation of reduction strategies including agronomic criteria (yields), environmental impacts and erosion of efficacy of fungicides, which depends on frequency of treatments.

The model is developed for the pathosystem wheat-Septoria, which is the major disease for wheat in France and Western Europe. This choice is also motivated by the facts that the control of Septoria is based mainly on chemical control that Septoria epidemics are influenced by canopy architecture and that architectural models already exists (Robert et al. 2008).

MODEL DESCRIPTION

The model is mostly based on the coupling of a series of already existing models. We use the OpenAlea platform (Pradal et al, 2008) to perform the coupling. This platform allows for importing models written in different languages, and to wrap them as python software components. One or several integrated models could then be built by chaining the execution of these components in a dataflow. The integrated model is also designed to avoid implicit dependences between components. To do so, all the communication between components is made through data reading/writing on a central structure representing the canopy.

Two main applications were built. A first application allows for the simulation, at an hourly time step of the development of wheat architecture, of Septoria epidemics dynamics, of fungicide application, of fungicide effect on Septoria infectious cycle and of the fate of fungicide on the leaves. It involves six main sub-models, each being divided in several components and connected together in a repeated hourly loop.

The principal sub-models were:

- ADEL-Wheat (Fournier et al., 2003). This model is based on the OpenAlea version of Adel-Wheat (Fournier et al. 2010) that allows for simulating 3D architectural wheat development at different stages. Two main improvements have been added: a new parameterization protocol that allows an automated fit from experimental data (Abichou et al., this volume) and (ii) a new simulation frame that allow for updating a canopy from a given existing state. This module creates or modifies an MTG representing the canopy at different scales, from organ to canopy.
- Septo3D-Cycle: This model simulates the growth of a lesion of Septoria. It has been extracted as an individual component from the Septo3D model (Robert et al., 2008). The model was extended to take into account the effect of fungicide, as described below
- A model of fungicide effect on disease dynamics, adapted from the model of Milne et al. (2007). This model allows for computing the global effect of a mixture of product, given their doses and parameters describing dose-response curve for each product. Dose-response curves describe two effects of a product on fungus: a protectant effect that decrease infection efficiency, and an eradicant effect that reduce the rate of development of the lesions.
- Septo3D-Dispersion: this model originates from Septo3D model (Robert et al. 2008), and was implemented as an independent component using the generic frame defined by Garin et al. (unpublished). It allows for simulating spores dispersal by rain, using a 1D multilayered approach.
- A model simulating fungicide interception. We use the projection algorithm included in the Caribu light model (Chelle et al., 1998) to simulate the surfaces reached by fungicide, together with the quantity of product hitting the surfaces. A physical model (Saint-Jean et al., 2006) is then used to predict the fraction of product that will effectively be fixed on the surface, splashed or leached. This model uses an experimental measurement of droplets size and velocity emitted from the nozzle of the application device.
- A model simulating the persistence of the fungicide on the leaf. We use a special version of the PEARL model (van den Berg, 2008) to estimate dynamically the fraction of product that remains active on the

surface, or that is lost due to penetration into the plant, volatilization or washing by rain. This model is called for every leaf elements in the canopy, using local micro-environment for light distribution and for rain intensity. These two variables were estimated using the Caribu model (Chelle et al, 1998).

A second application evaluates impacts based on the simulation results of the first application. Three impacts were considered:

- Impact on crop performance (yield) is estimated using a model, based on empirical laws established for wheat (Bancal et al., 2007).
- Environmental impacts are computed using standard versions of PEARL (van den Berg 2008) and PRZM (Carsel et al, 1998) models.
- Erosion of fungicide efficacy is estimated as a function of the number of selection events encountered by fungus exposed to products.

RESULTS AND DISCUSSION

This study allowed building an integrated application that can be used for assessing several strategies of reduction of fungicide application, with an emphasis on canopy architecture effects. The model results from an assembly of several sources, developed in different laboratories for different uses. OpenAlea plateform was particularly suited to achieve such collaborative integration, with support for coupling, documenting and testing. Our first objective was to get an operational integrated model, and this will be demonstrated with simulations of simple scenarios. In a future study, the model will be used for assessing different application strategies. Here, we rather tried to perform partial validation and calibration of each sub models. Occasionally this required an assembly of components slightly different from the integrated model. Partial validations were done by comparing simulation results with experimental data, or by qualitative assessments of model behavior by experts. These validation results include a comparison of the simulated canopy with photographs, a comparison of simulated fungicide interception in the canopy with experimental data, and an overall assessment of the behavior of the models regarding epidemic dynamics as a function of the date of application

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