Integrating pests into crop models: a modelling framework

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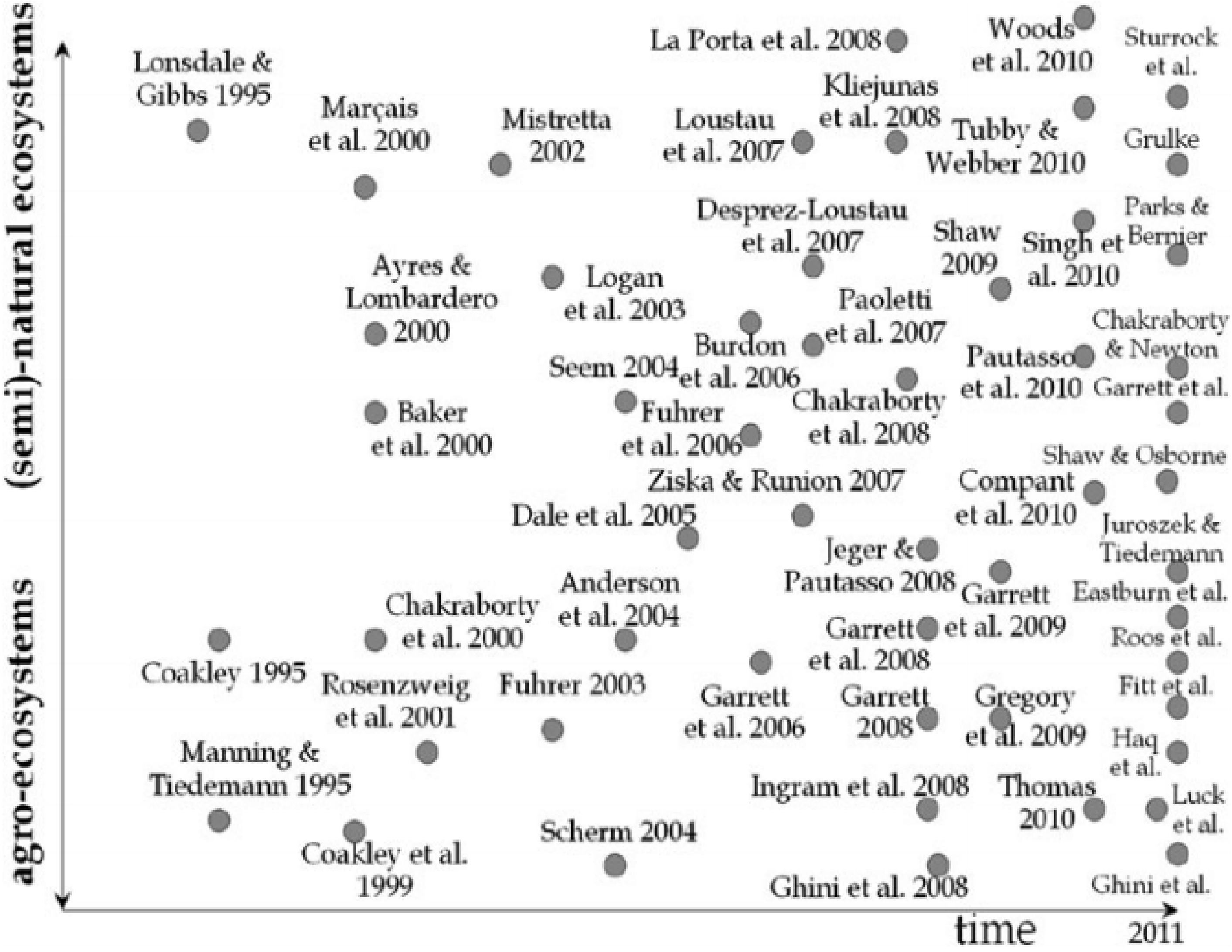
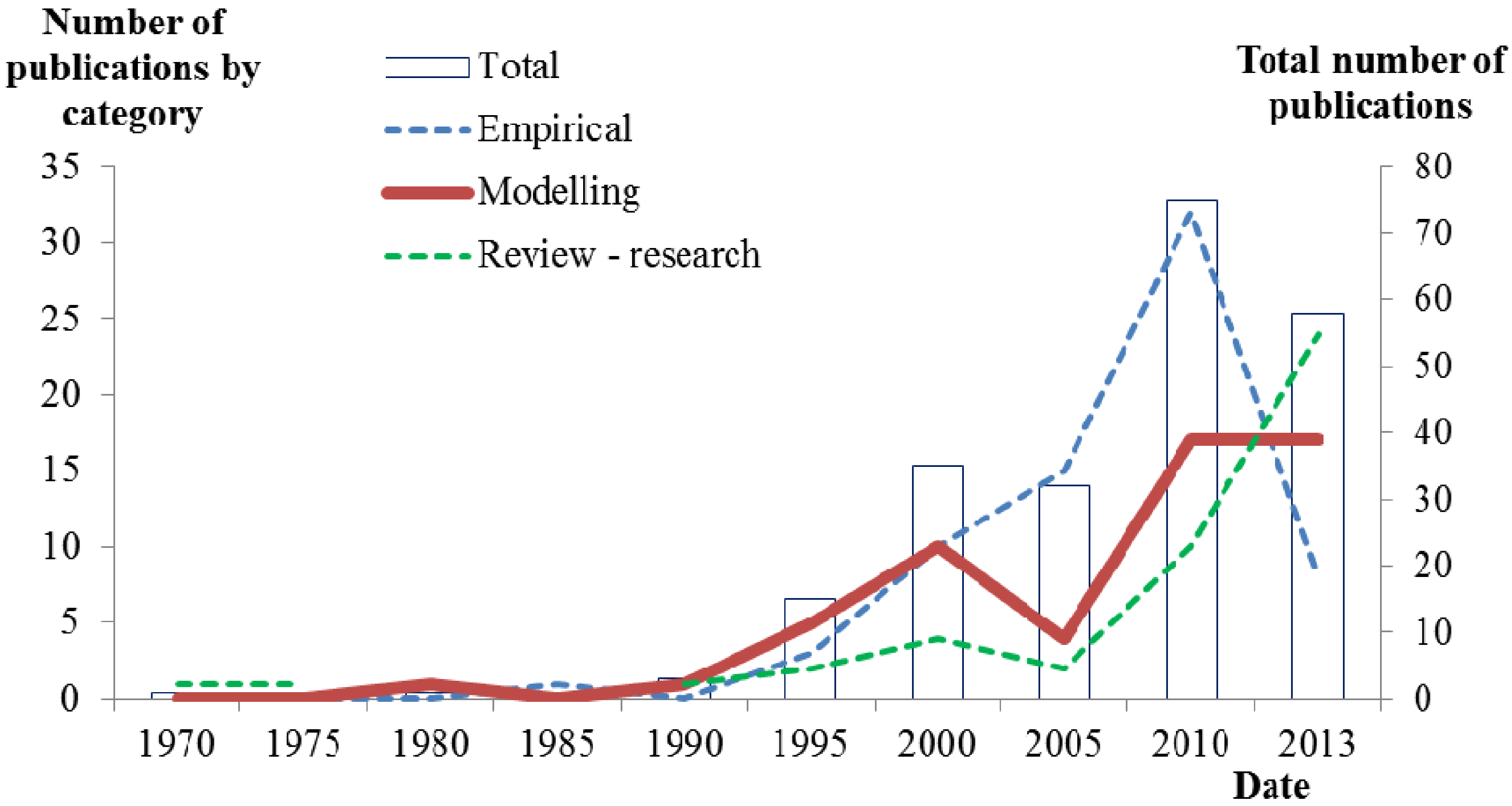
Climate change and plant diseases

- The analysis of the impacts of climate change on plant diseases started in the 90' (Pautasso et al., 2012)
- Many authors state that the assessment of host-pathogen interactions requires a case by case evaluation (Coakley et al., 1995).



Pautasso et al., 2012

Content of papers



Re-elaborated from Chakraborty (2013)

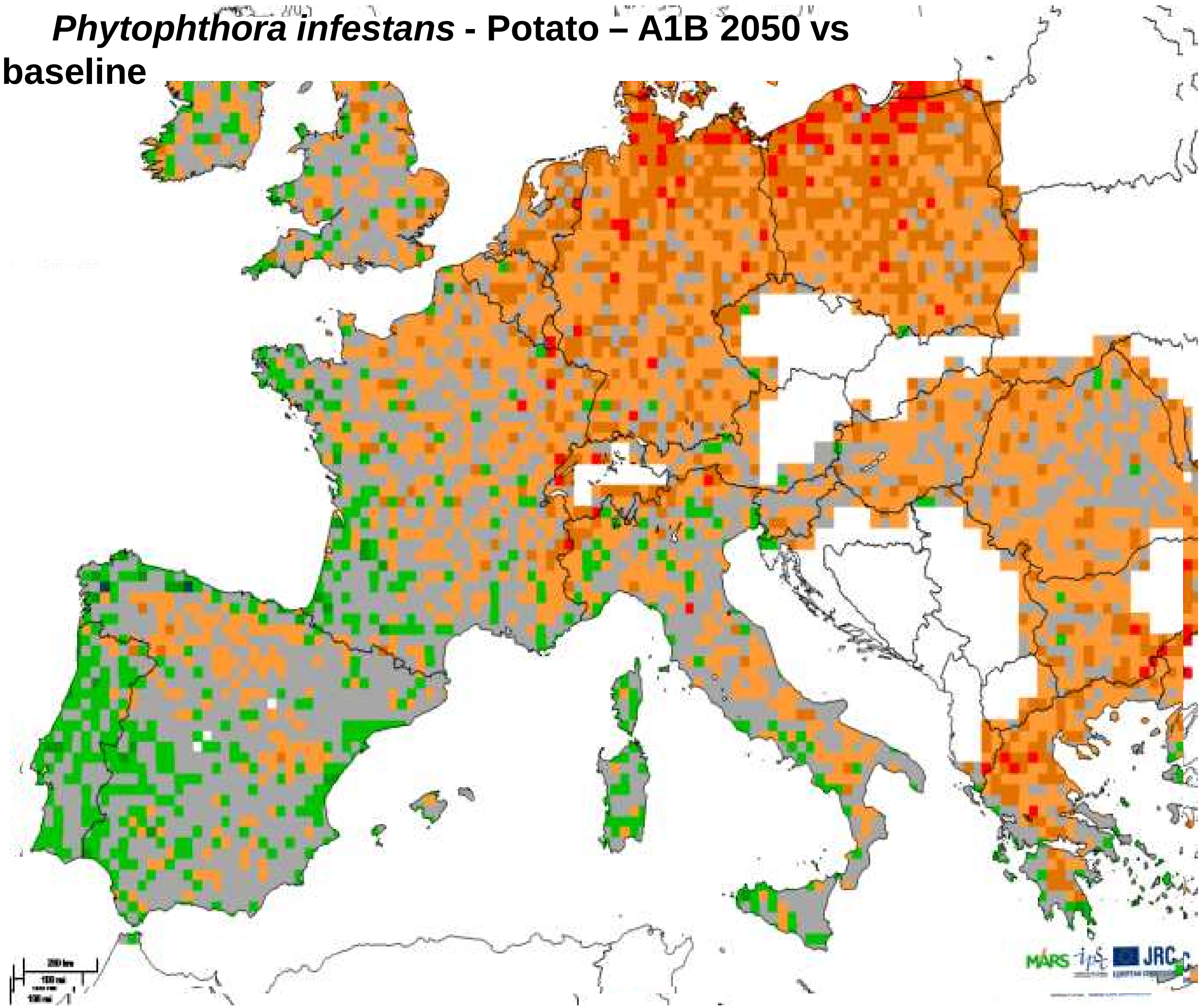
Main open issues from literature

"Findings on climate change influence on plant pathogens are often inconsistent and context dependent. Knowledge of pathogens affecting agricultural crops and natural plant communities remains fragmented along disciplinary lines."
Chakraborty, Global Change Biology (2013) 19, 1985–2000

	Climate signature	Phatogen biology, ecology & epidemiology
Relevance	• Reduce uncertainty • Improve models • Justify research investments	• Management to target pathogen vulnerability • Maintain food security
Limitation	• Very few studies • Data sources from long-term experiments are ignored • No use of historical data to predict future trends	• No multifactorial study • No data of extreme weather impact • Knowledge of biology and life cycle is fragmented

A diversified future…

"The effect of changin
individual pathosyster
Garrett et al., Annu. R



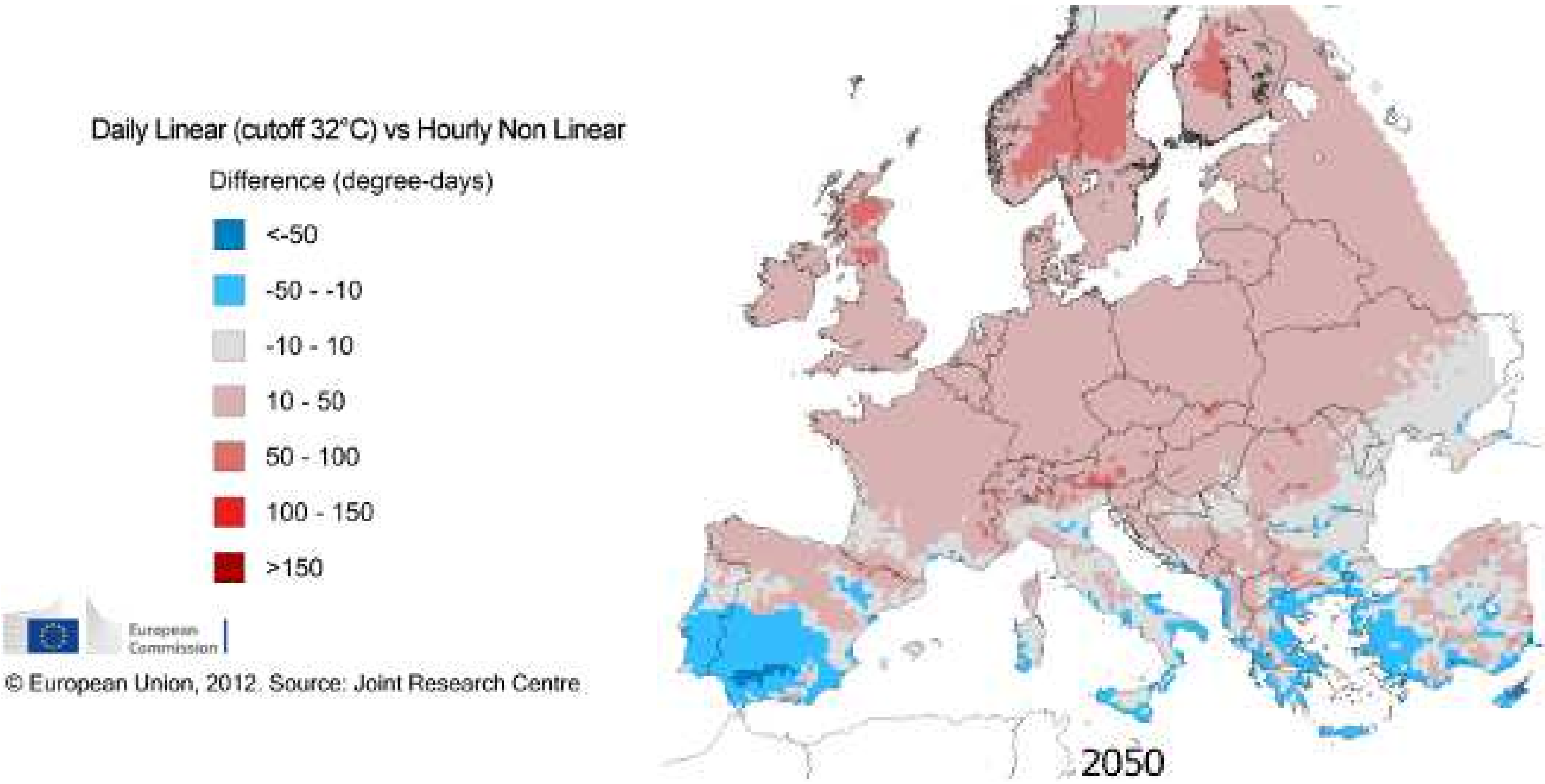
- infection events

no variations

+ infection events

Magarey et al.' model of potential infection, 2005

Temperature responses



An integrated (integrable) system

In practice, it may be necessary to expand models to include more components, identify those components that are the most important, and synthesize such models to include the optimal level of complexity for research prioritization.
Garrett et al., Plant Pathology (2011) 60, 15–30

…linking of pathogen dynamics, crop growth and climate models is essential in predicting disease risks under climate change.
Pangga et al., Plant Pathology (2011) 60, 70–81

- The target is set as using a modelling framework, possibly further stressing on:
  - Extensibility
  - Reusability of modules
  - Libraries of known crop/diseases approaches
  - Transparency

- Building a framework matching those requirements (and others) has been technologically at reach since many years!

Right answers for wrong reasons

- Even limiting to crop models, data for thorough model testing have always been a limiting factor.
- For applications which do not allow using statistical models, we use process-based models which require rich reference dataset, to avoid merely fitting data – setting parameter values which provide an acceptable matching to reference data, but which are almost meaningless.
- Including in the picture disease models and their impact increases the requirements for valid dataset, hence making the problem even bigger.
- Collecting data to develop models for generic reuse – which is not fully equivalent to collect data for context specific applications, remains a limit difficult to overcome but a prerequisite for improving model predictive capabilities.

The Diseases software package

A MODELLING FRAMEWORK

Introduction: constraints

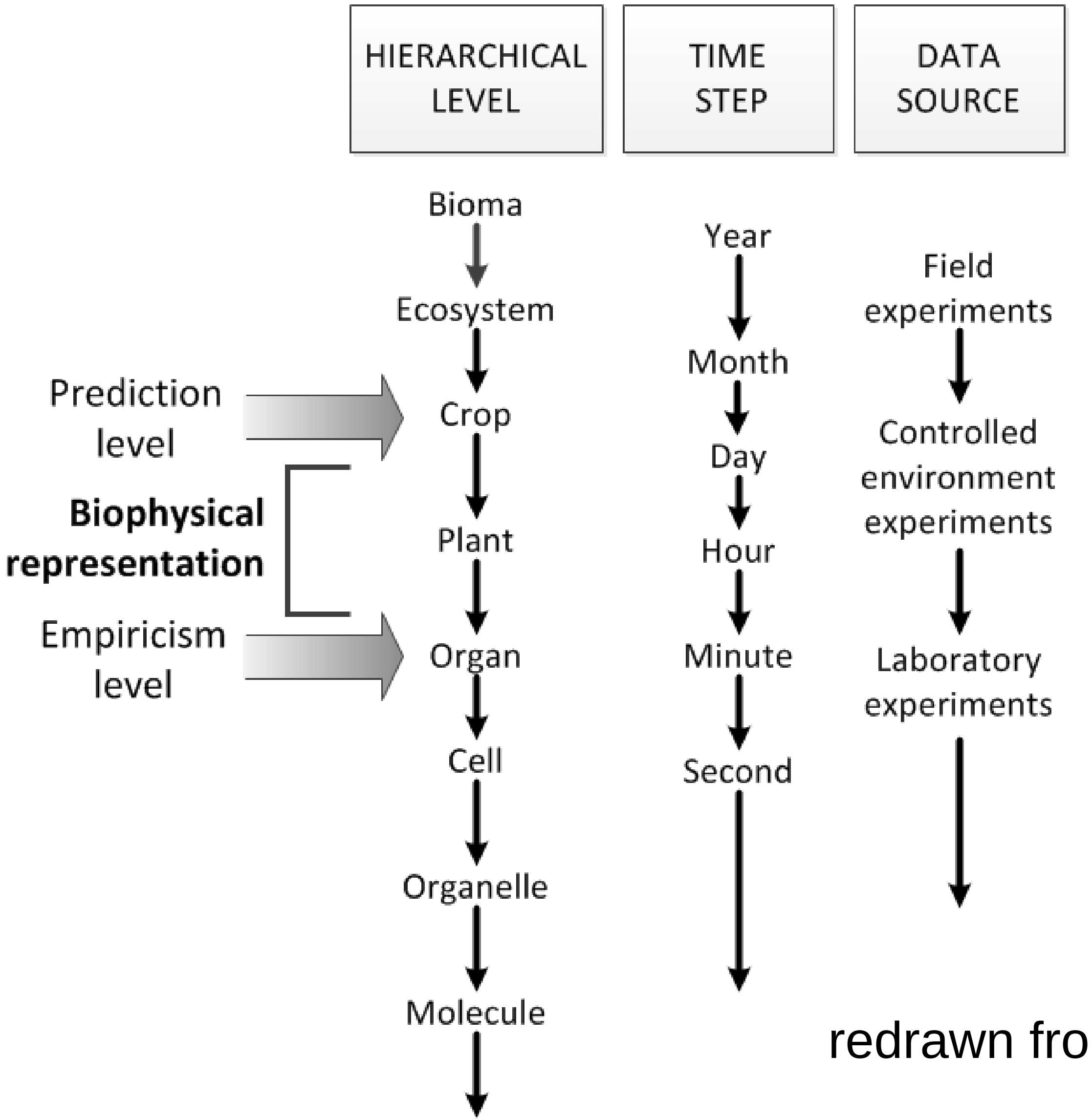
- The simulation of crop performance under climate change scenarios includes, as one of the assumptions, the likely lack of adaptation of crops to the new environmental conditions.
- Climate impacting on crops is no longer “known variability”, but it might include extremes and new patterns of temperatures and rainfall, which increase the risk of relying on observations to estimate future trends of crop responses.
- Process-based crop models need to be verified in terms of assumptions accepted in the formalization of processes, often implemented as simplifications of responses.
- Plant diseases models are no different; moreover, site and weather-specific interactions with crops may substantially change under new scenarios.

Introduction: approaches

- Simplifying the impact of diseases on crop performance in unknown weather conditions should not be done as reduction on yield *ex-post* because:
  - There is no knowledge of what the impact (of what disease?) could be under “unknown” patterns of weather variables;
  - Ex-post corrections introduce an error in estimating use of resources during growth, which would impact substantially on yield in conditions, for example, of water scarcity;
  - The development of agro-management plans, direct to control diseases, and indirect to supply crop inputs, are affected, making the development of adaptation techniques biased.

- The level of empiricism in building modelling solutions is a limiting factor for future, unknown conditions: there is no data to build and corroborate the empiricism.

Level of empiricism and prediction



redrawn from Acock and Acock, 1991

Aim of the framework

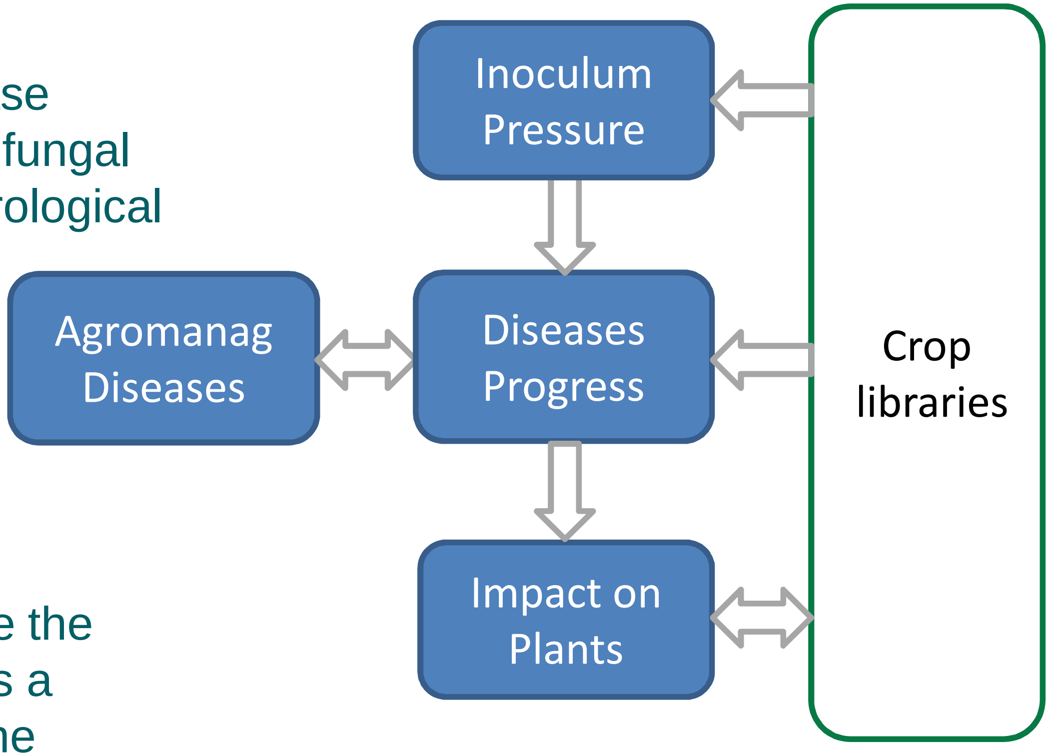
- To develop capabilities of simulating diseases and their interaction with crops under climate change scenarios:
  - The framework had to be based on process-based simulation, less risky under unknown conditions once system analysis evaluates modelling approaches in the target context;
  - It had to be extensible to allow for alternate and new approaches to simulate diseases and crop-disease interactions;
  - The simulation of agro-management had to be included to allow developing plans for technical adaptation;
  - The system had to be open, to allow plant pathology modelers to extend and using the framework for specific cases, hence contributing via a building block approach.

Outline

- The Diseases framework modules
- The software implementation
- Applications
- Conclusions

Modules of the framework *Diseases*

- The ***Diseases*** components are four software extensible libraries implementing models to simulate the time evolution of a generic air-borne fungal disease epidemic:
  - **InoculumPressure**, to estimate the time of the disease onset and to provide models to derive initial disease severity.
  - **DiseaseProgress**, to simulate the disease progress rate of a monocyclic/polycyclic fungal disease as a function of the agro-meteorological conditions and of the plant-pathogen interactions.
  - **ImpactsOnPlants**, to simulate the impact of a diseases epidemic on plant processes and organs via the coupling to crop models.
  - **AgroManagementDiseases**, to simulate the reduction of the disease progress rate as a function of a chemical application, and the decay of the effectiveness of the active principle.



The whole picture: model libraries

BIOMA

Weather libraries

AirTemperature, EvapoTranspiration, LeafWetness, SolarRadiation, Rainfall, Wind
Climatic indices
Weather Generators (ClimGen, CLIMAK)

Abiotic stresses

Heat damage, Rice cold shocks, Lodging

Biotic stresses

Generic air-borne diseases simulator (Diseases, Magarey), Generic soil-borne diseases growth (SBD), CornBorer simulator (MYMICS)

Chemicals

Chemicals dynamics (AgroChemicals)

Plant libraries

Generic crop simulators (Wofost, CropSyst, STICS)
Generic tree simulator (Tree)
Rice (WARM)
Sugarcane (CaneGro)
Grain quality (AgPro-Q)

Soil libraries

Soil water runoff and erosion (CN, Eurosem),
Soil water redistribution (Cascading, FiniteDifferences)
Soil surface and profile temperature,
Soil nitrogen (SoilN)
Pedotransfer functions (SoilPAR)

Agricultural management

Rule-based modelling (AgroManagement)

The *InoculumPressure* module

- The modelling of density, dispersion and type of primary inoculum is crucial for the simulation of a plant disease epidemic (Andrade-Piedra et al., 2005).
- The timing of symptoms onset and the initial disease severity vary across environments and growing seasons, and depend on the agro-environmental and management factors during the period when the crop is not in the field (Gupta, 2004).
- Simulating spores dispersal accounting for the above is a demanding effort, given that many pathogens differentiate
  - sexual spores to survive during fallow periods;
  - asexual spores to repeat secondary cycles during the cropping season, with different thermal and wetness requirements (Rapilly, 1991).

The *InoculumPressure* module

- The module allows estimating the time of the disease onset and to provide models to derive initial disease severity.

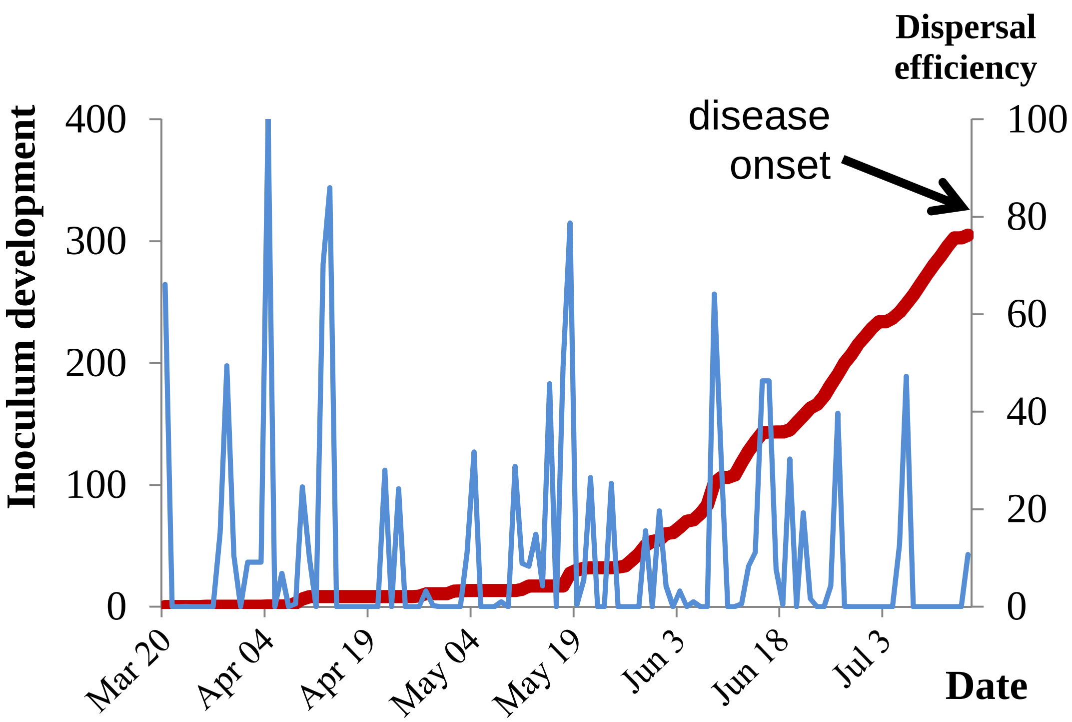
- The module implements models to simulate:
  - the time of disease onset based on hydro-thermal time (Rossi et al., 2008);
  - the infection and sporulation efficiencies of primary inoculum (Magarey et al., 2005; Launay et al., 2014)
  - spores dispersal as driven by wind speed or precipitation. (Waggoner and Horsfall, 1969; Aylor, 1982)

- Models can be added to simulate inoculum survival during fallow periods (as well as alternate options to estimate initial disease severity).

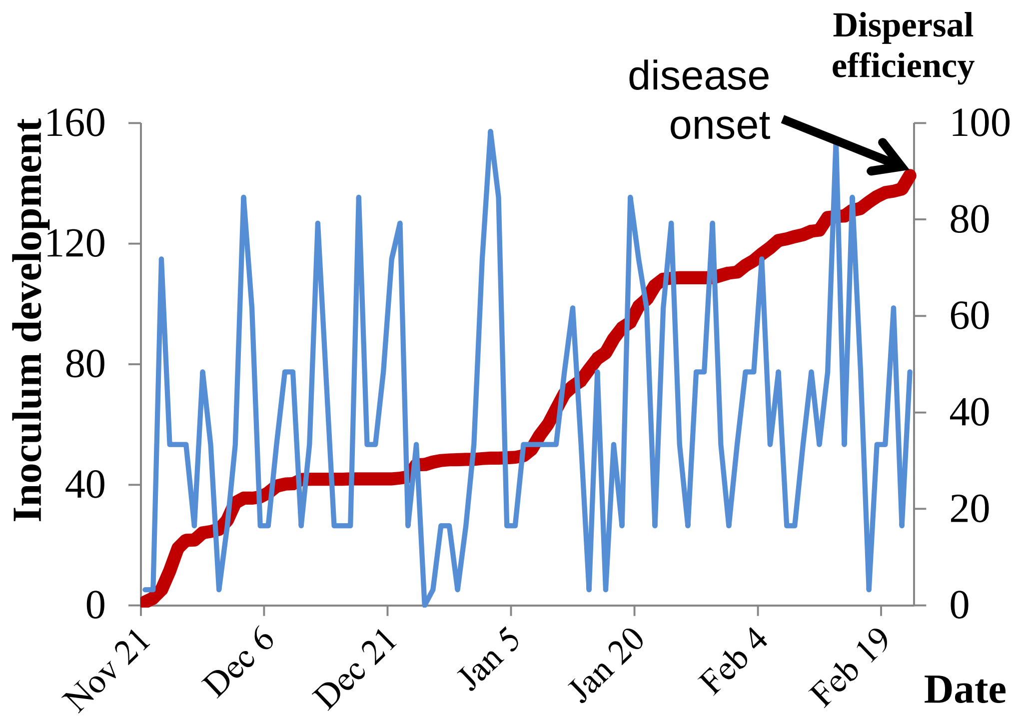
Timing of the disease onset

- Hydro-thermal time is accumulated hourly considering threshold temperatures for inoculum development and a threshold of hourly air relative humidity limiting accumulation.

Blast on rice

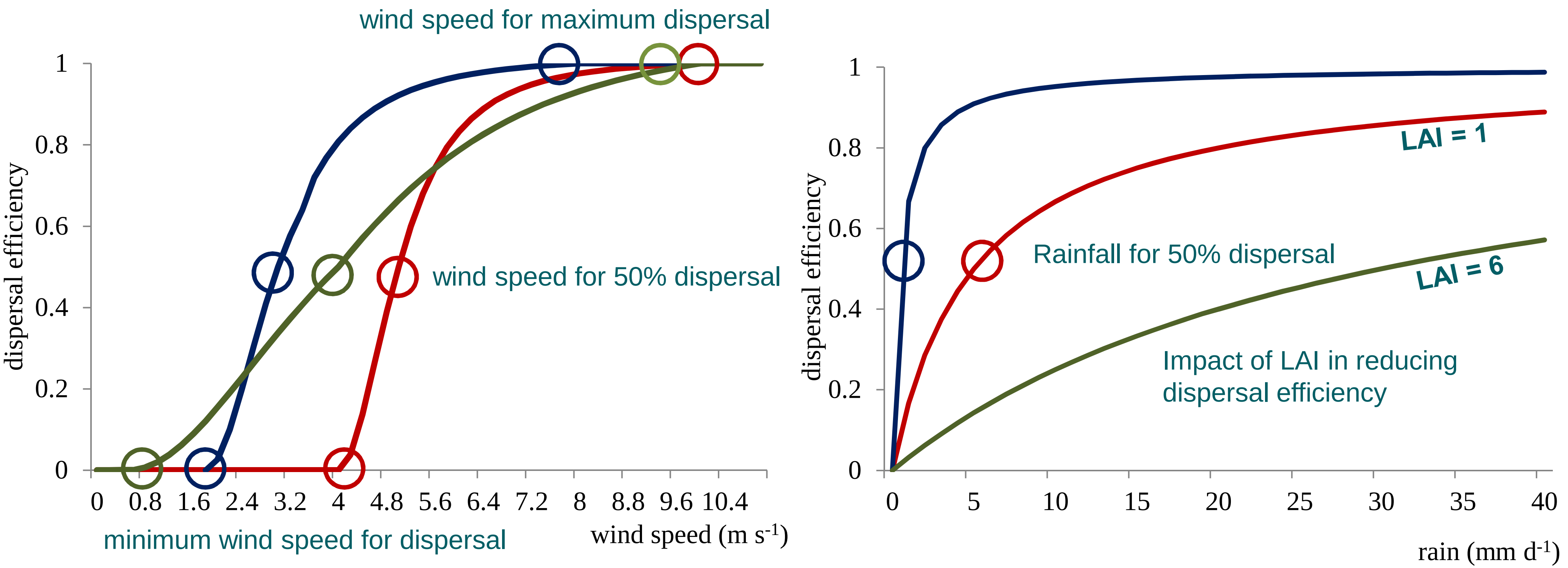


Brown rust on winter wheat

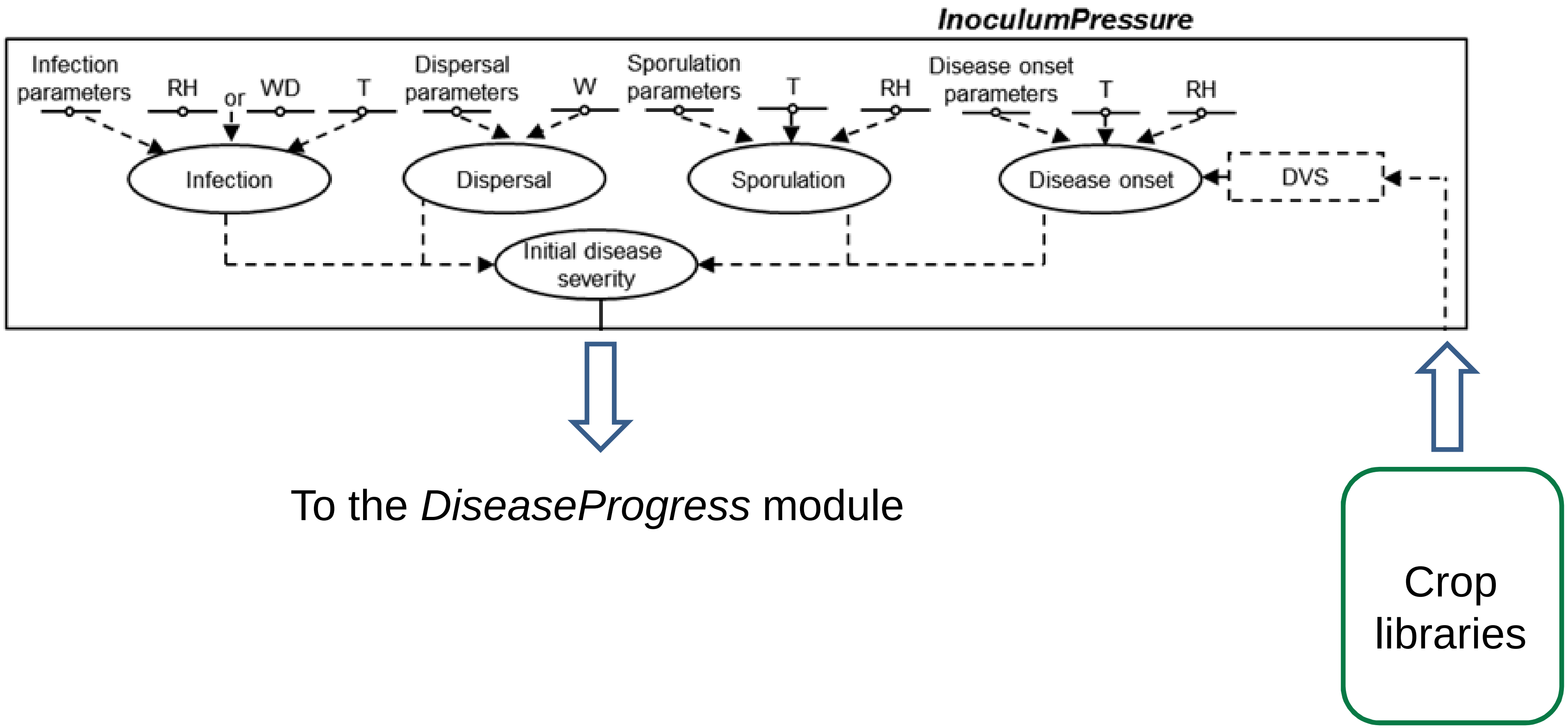


Wind and rain spores dispersal

- These functions can be parameterized by setting few parameters with a clear biophysical meaning.
- Parameters can be found in literature or measured in dedicated experiments.



The *InoculumPressure* module

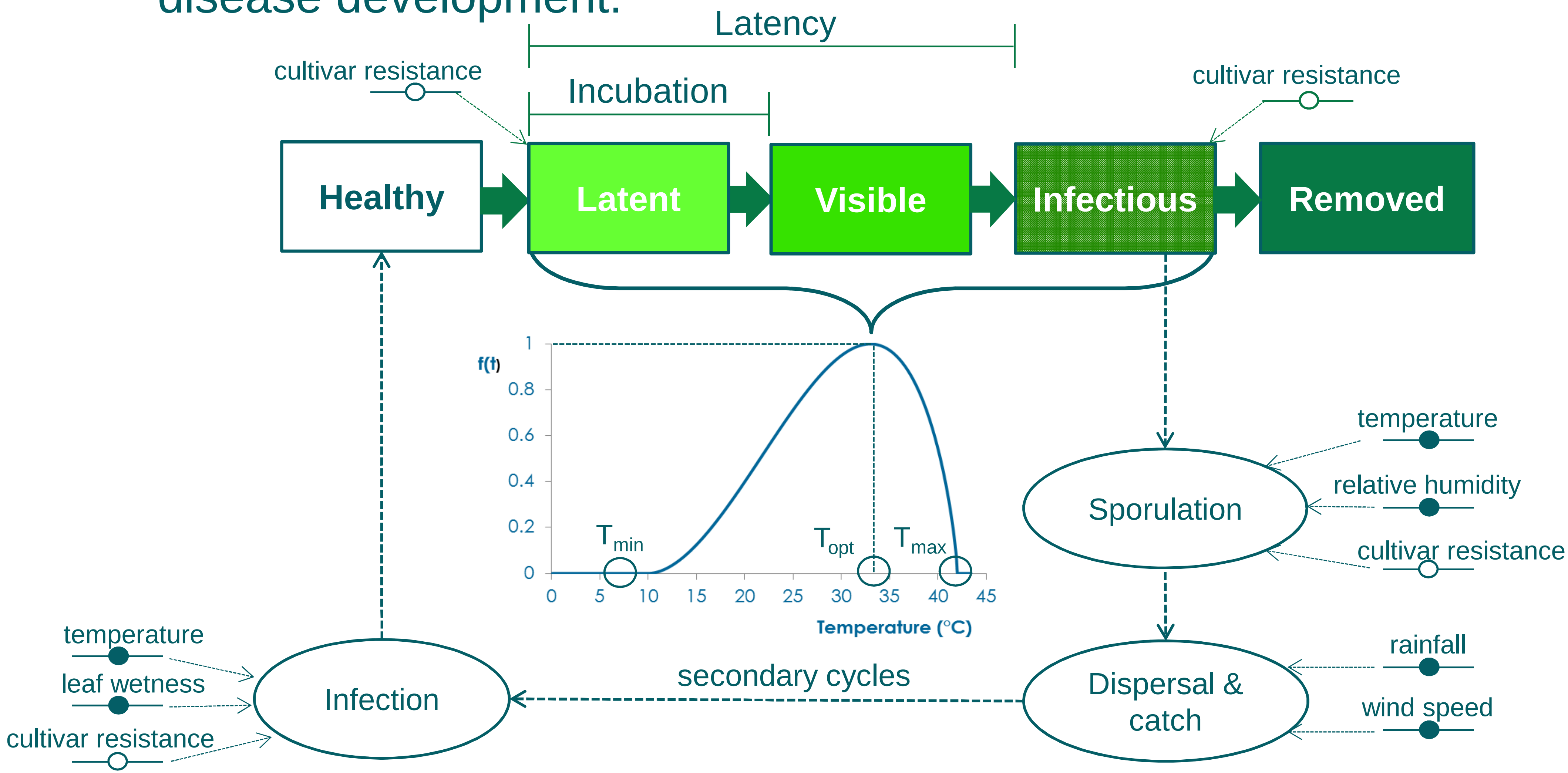


The *DiseaseProgress* module

- The approach used for impact simulations on the host tissue is based on the development of Susceptible-Exposed-Infected-Removed (SEIR) models.
- The plant host tissue which can become infected is consequently classified into non-overlapping categories such as *healthy*, *latently infected*, *visible but not sporulating*, *infectious* and *sporulating and removed* (Jeger, 2000).
- The parameters in SEIR models usually drive functions of exogenous variables such as air temperature, leaf wetness, wind speed, rain and air relative humidity (Ferrandino, 1993).
- The level of host resistance and the variable susceptibility of host tissue during the crop growth are important factors to be considered in modelling (Shtienberg, 2000), since they affect the rate of disease development during the cropping season.

The *DiseaseProgress* module

- The host tissue is divided into compartments according to disease development:

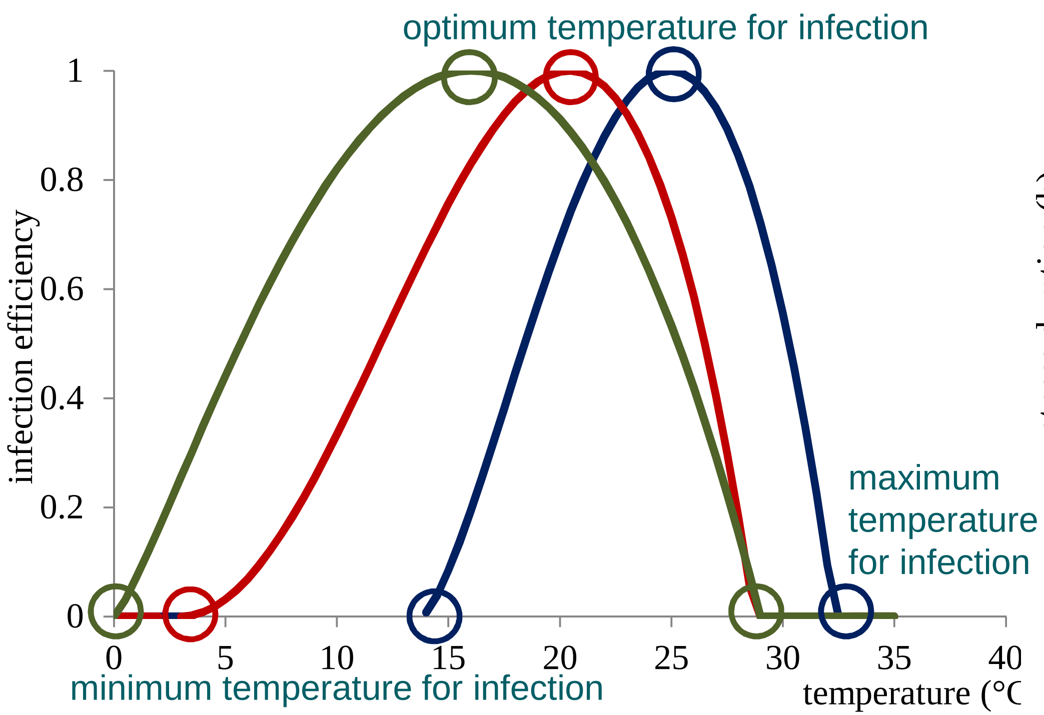


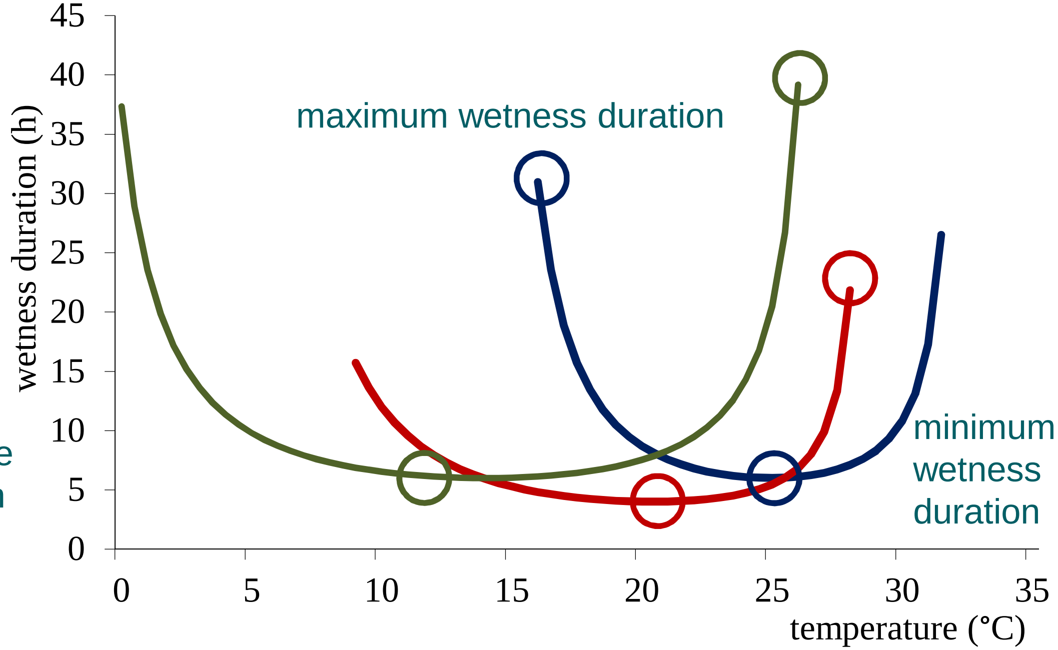
Diapositive 23

S3 Manca animazione, va rifatta
Simone; 15/02/2015

Infection – temperature and wetness requirements

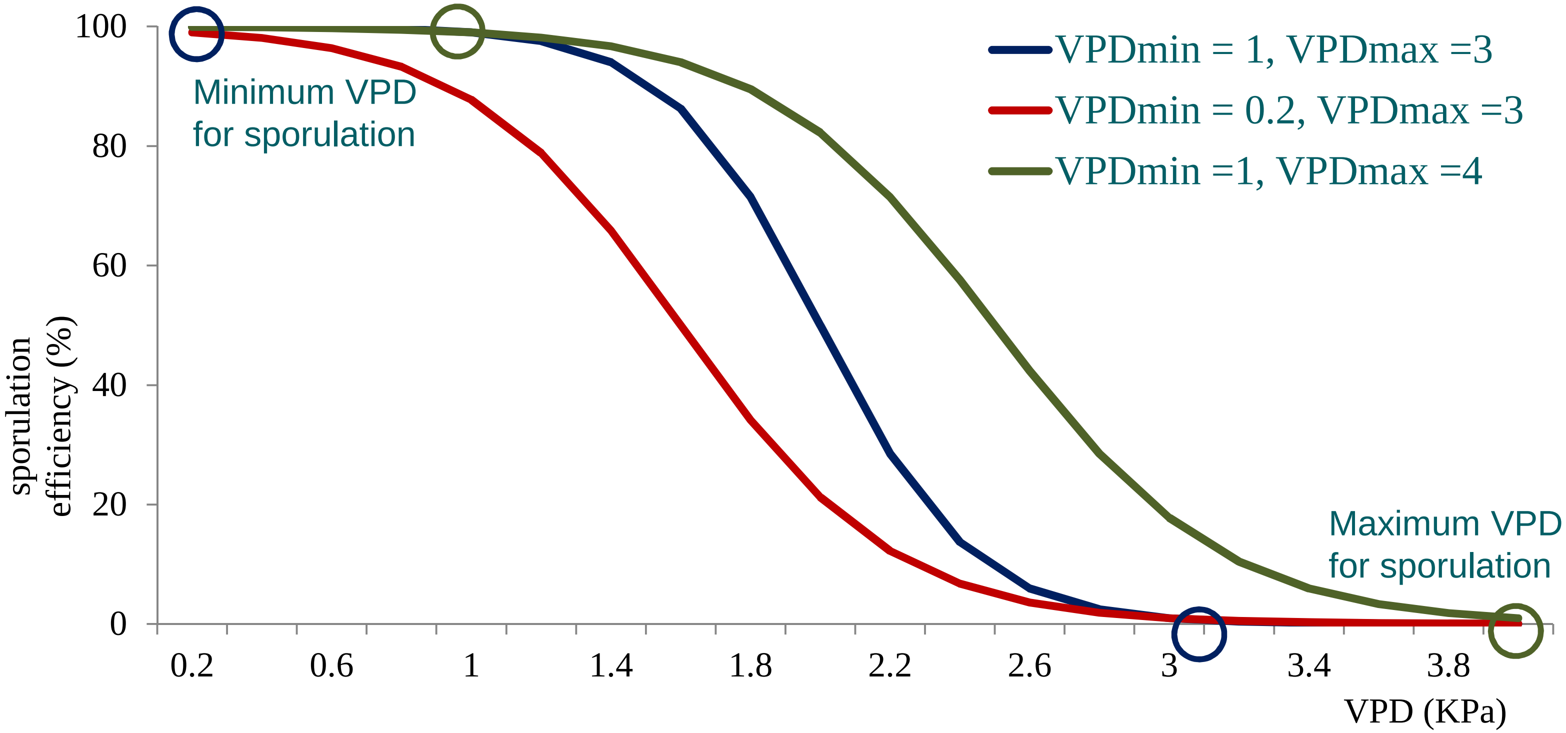
- The temperature response function is parameterized according to the thermal requirements of different pathogens.
- The model considers the minimum and the optimal duration of the wetness period.
- The number of hours needed to complete an infection event (Magarey et al. 2005) is used to derive daily infection efficiency.





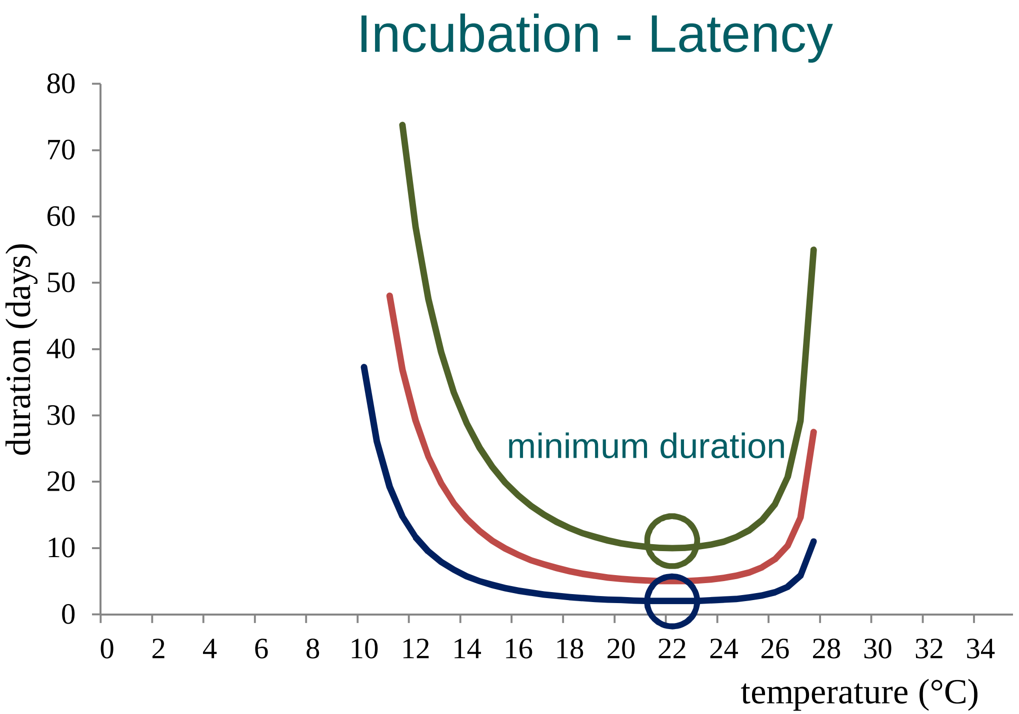
The *DiseaseProgress* module

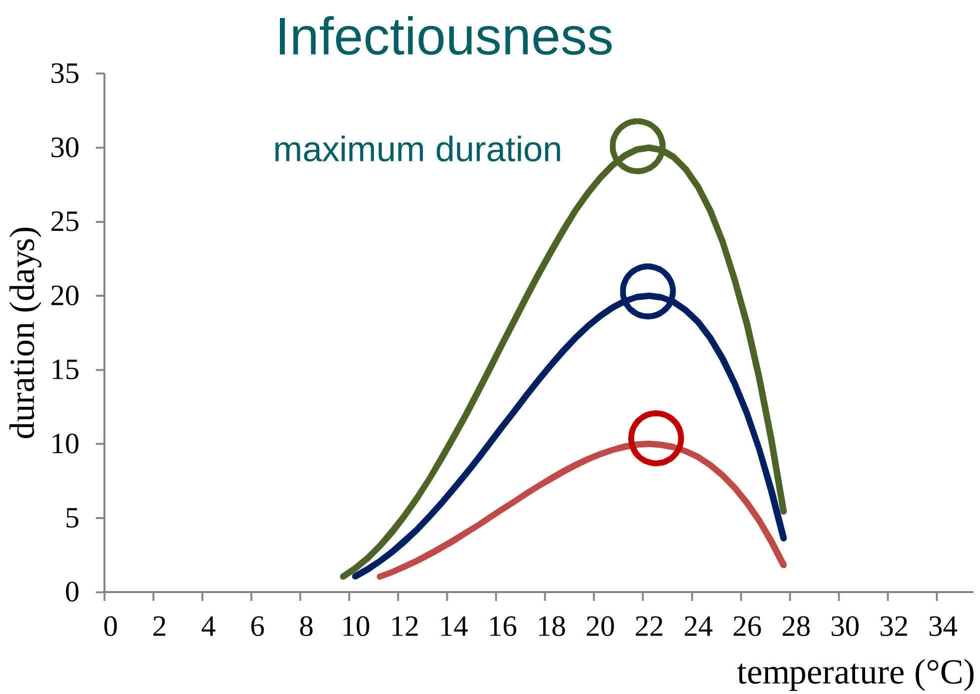
- Sporulation efficiency is computed basing on temperature and vapour pressure deficit or relative humidity (as a threshold)
- The same temperature response function as for infection can be parameterized for the sporulation process.



The *DiseaseProgress* module

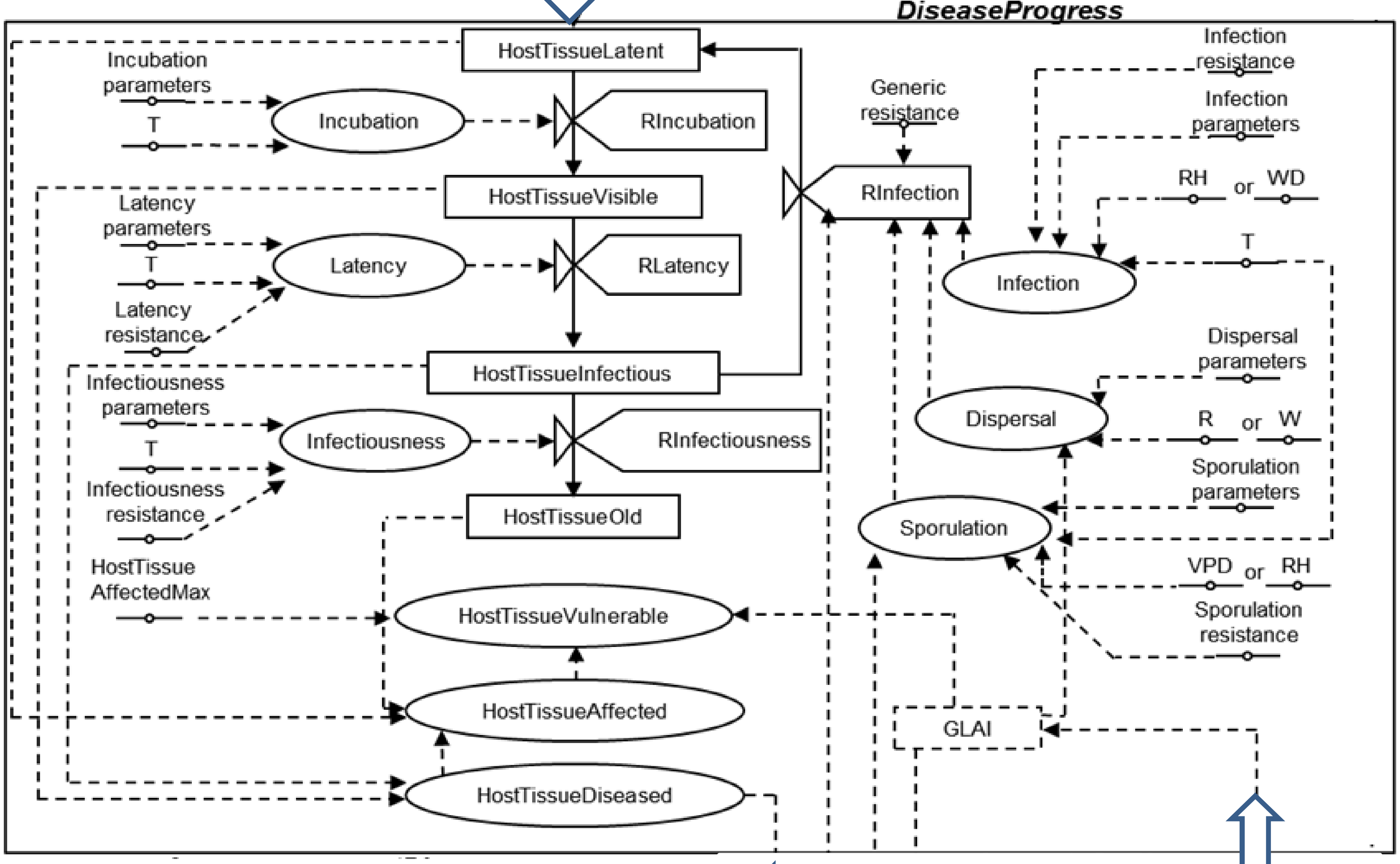
- The duration of the latency, incubation and infectiousness periods is simulated as dependent by hourly temperature.
- Parameters needed are cardinal temperatures for the periods and duration (days) of the period at optimal temperatures





The *DiseseasesProgres* module

From *InoculumPressure*



Crop libraries

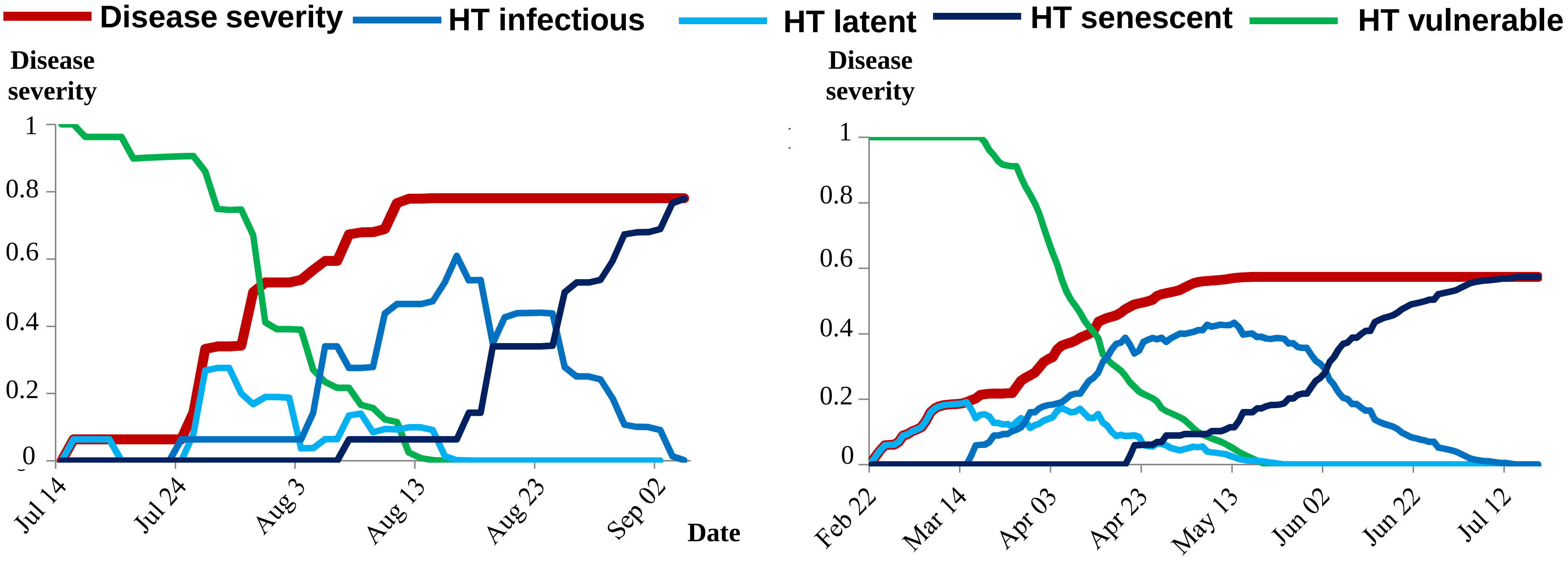
To *ImpactOnPlants* and *Agromanag*

Development: host tissue

- Models were parameterized to reproduce two pathosystems
- Two crop models, WARM and WOFOST
- Outputs of sample simulations to show model responses

Blast on rice
(crop model WARM)

Brown rust on winter wheat
(crop model WOFOST)



The *ImpactOnPlants* module

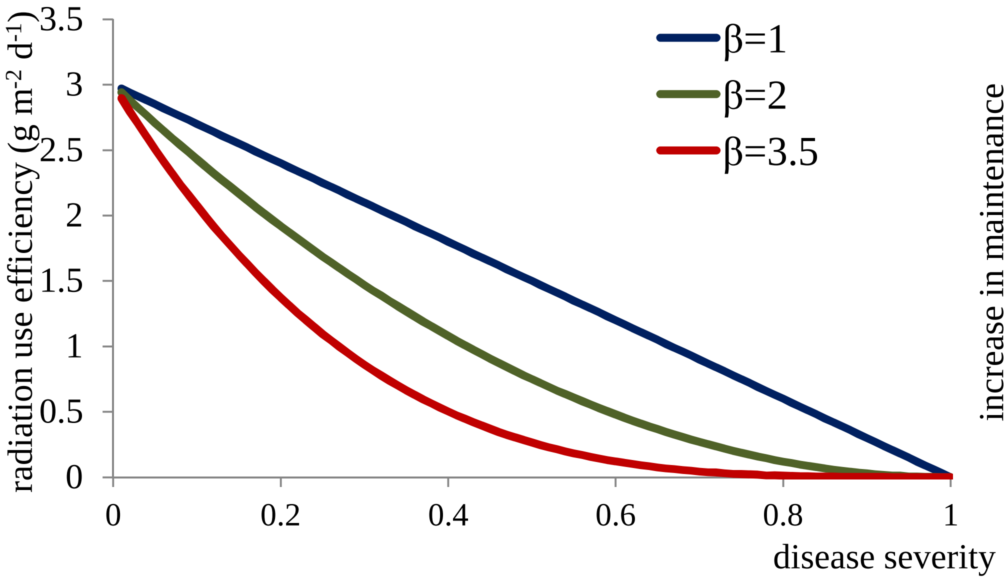
- The assessment of crop yield losses is indicated as the reason of existence of plant pathology (Fargette et al., 1988; Savary and Cooke, 2006).
- The reproduction of the damage of the disease on crop organs by linking the outputs of disease models to crop simulators (Pinnschmidt et al., 1995) allows a more realistic simulation of the crop-pathogen interactions (Johnson and Teng, 1990) than reducing directly states of either yield or biomass.
- The impacts of the disease on plant physiological processes (Boote et al., 1983) is taken into account via coupling points linking disease estimated rates to plant either states or rates.

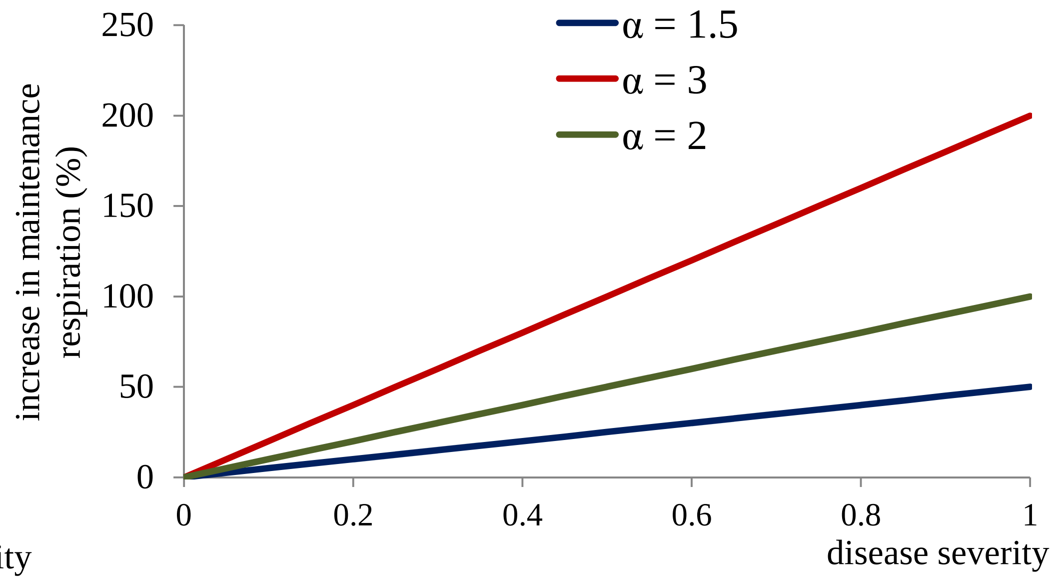
The *ImpactOnPlants* module

- The mechanisms of damage caused by fungal foliar pathogens can be grouped into two broad categories: the impacts on radiation interception and the impacts on the photosynthetic activity (Johnson, 1987).
- The reduction of the photosynthetic rate as a function of disease severity can be described using the concept of “virtual lesion”, (Bastiaans 1991), which corresponds to the visible lesion and surrounding symptomless tissue, plus any non-colonized region in which photosynthetic metabolism is affected.
- Another coupling point between crop models and disease models was developed to take into account the enhancement of the maintenance respiration as a function of the disease severity (Bingham and Topp, 2009).

The *ImpactOnPlants* module

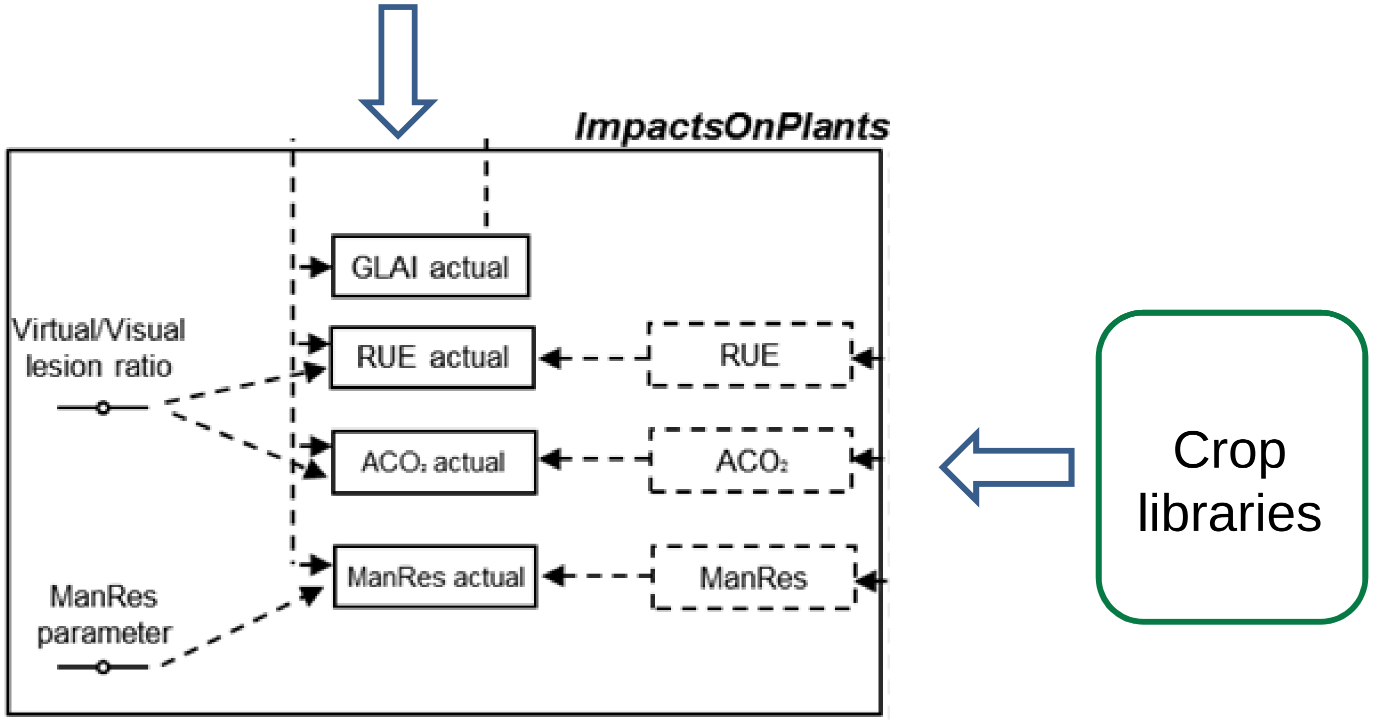
- Responses of the models to simulate the decrease of radiation use efficiency and/or the leaf CO2 assimilation as a function of disease severity and virtual-visual lesion ratio (β).
- Responses of the models to simulate the enhancement of maintenance respiration as a function of disease severity and of the ratio between the respiration rate of a lesion and that of an identical area of healthy leaf tissue (α).





The *ImpactOnPlants* module

From the *DiseaseProgress* module

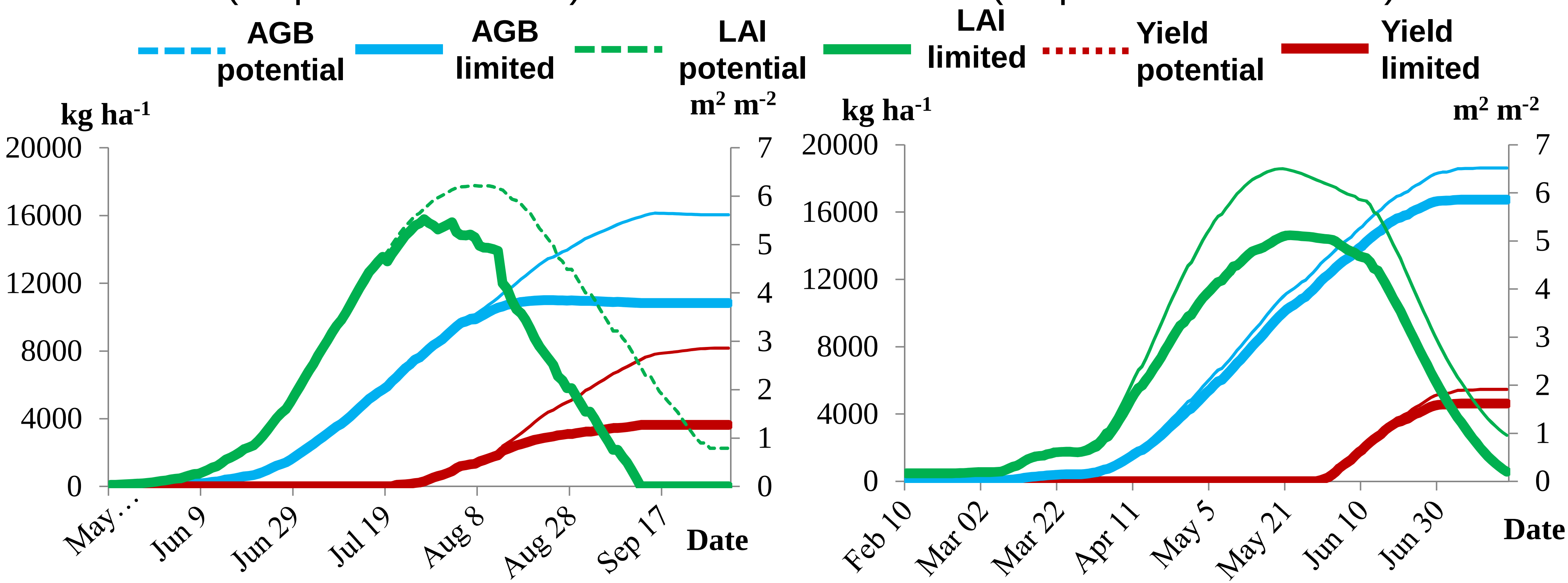


Development: biomass and LAI

- Leaf area index is dynamically reduced according to disease severity increase
- Impact on aboveground and yield.

Blast on rice
(crop model WARM)

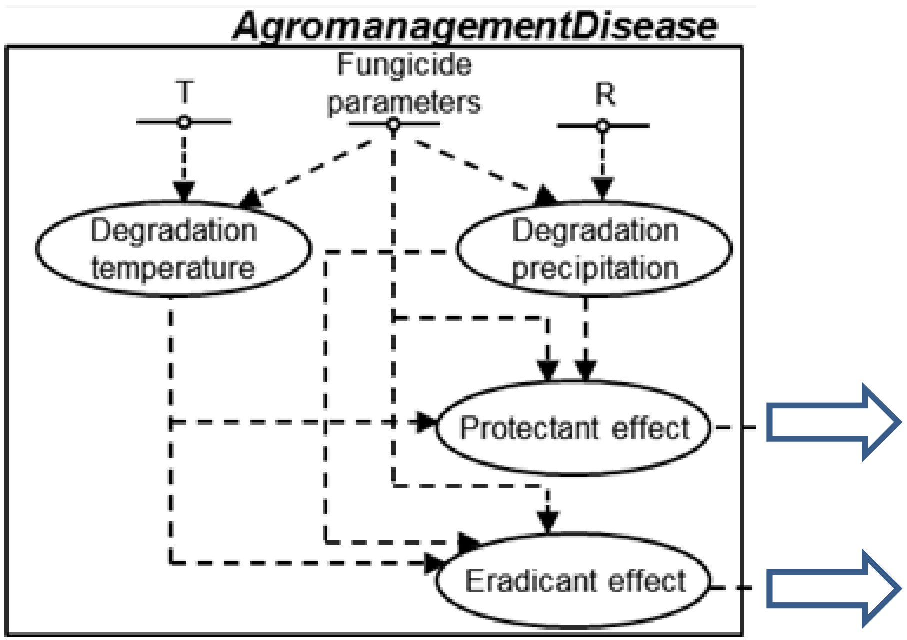
Brown rust on winter wheat
(crop model WOFOST)



The *AgromanagDisease* module

- The effects of chemicals on foliar diseases development can be grouped into two main categories (Milne et al., 2007):
  - protectant fungicides, which inhibit spore germination thus reducing the infection frequency (Manners, 1993; Russell 2005)
  - eradicant fungicides, which slow down the growth of mycelium and consequently the sporulation rate (Vyas, 1984; Bailey, 2000).
- Agro-management is currently implemented, like in all agro-management implementations in the BioMA platform, as:
  - Rules, to trigger agro-management events, based on the state of the system;
  - Model to estimate degradation of chemicals;
  - Impact models, which affect the states of the pathogen.
- Both rules and impact models are extensible.

The *AgromanagDisease* module

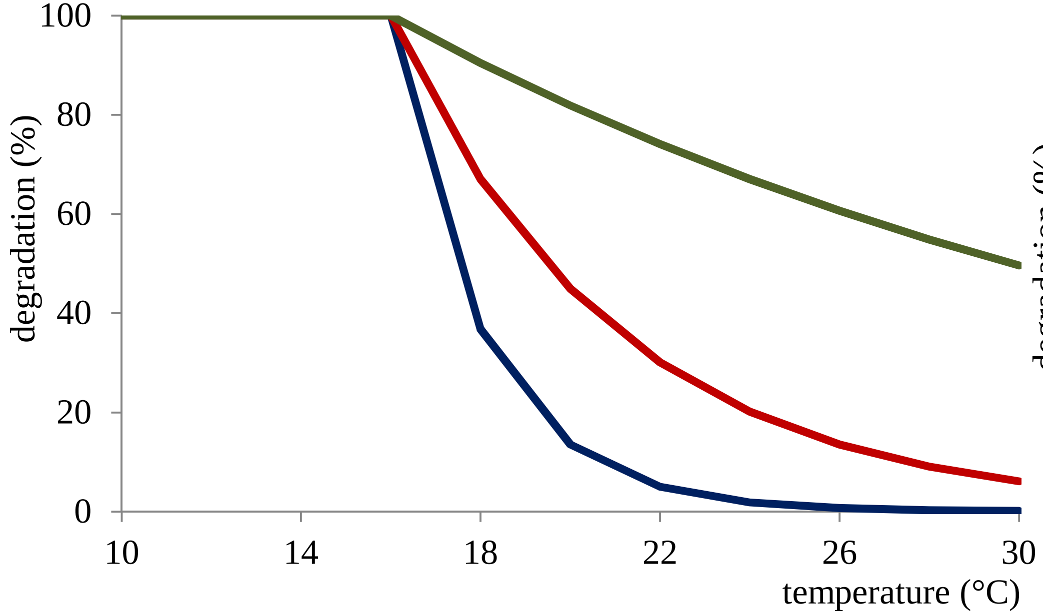


To the module
DiseaseProgress

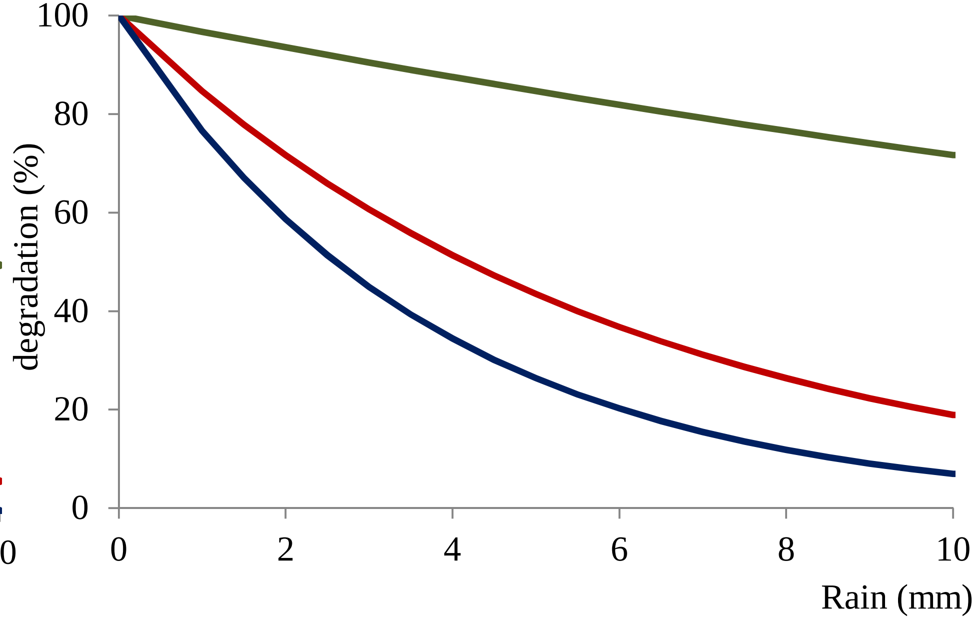
The *AgromanagDisease* module

- The degradation of the fungicide after chemical treatment is simulated as a function of
  - temperature (Patterson and Nokes, 2000)
  - rainfall (Arneson et al., 1978; two models)

Temperature degradation

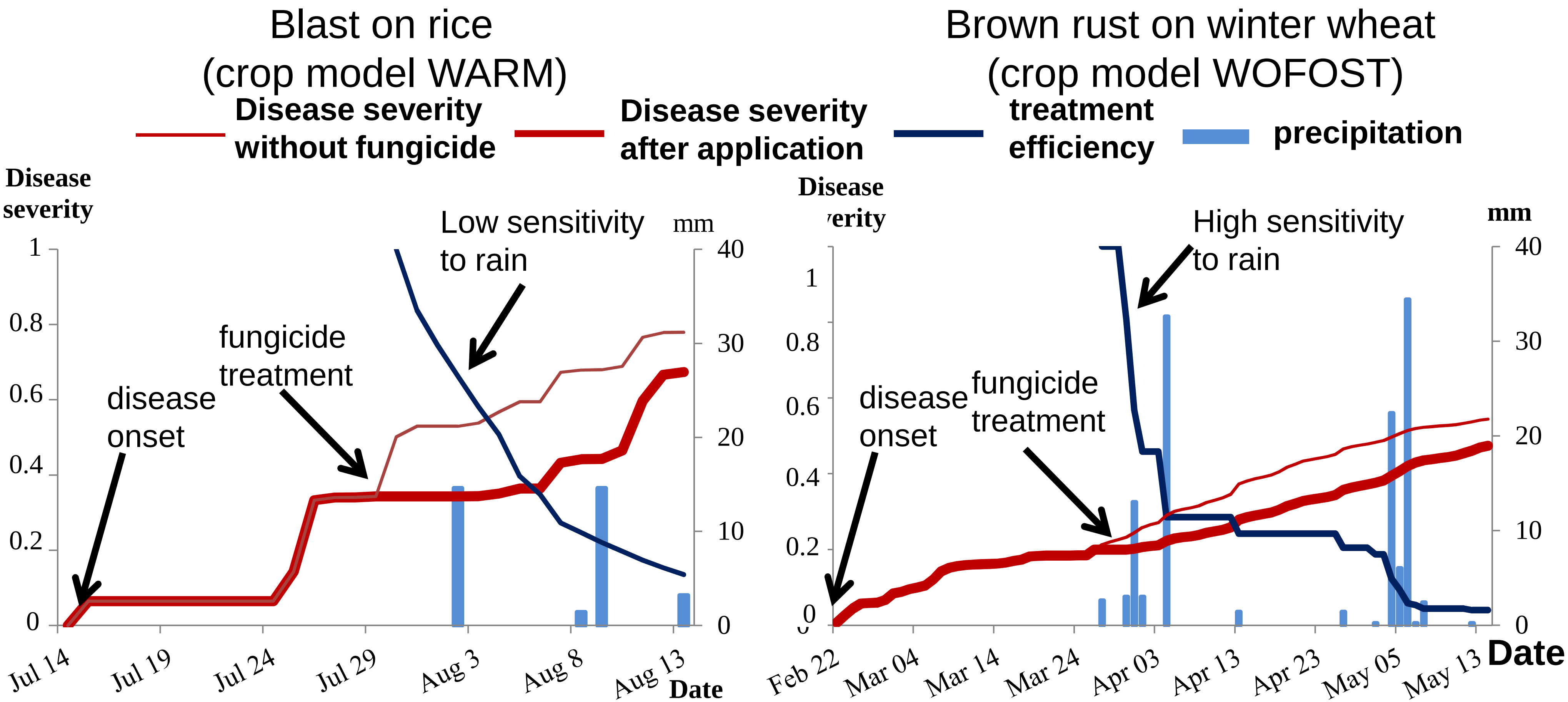


Rainfall degradation



Development: agromanagement

- Disease severity is reduced after chemical treatment
- The effectiveness of the chemical treatment is reduced after application



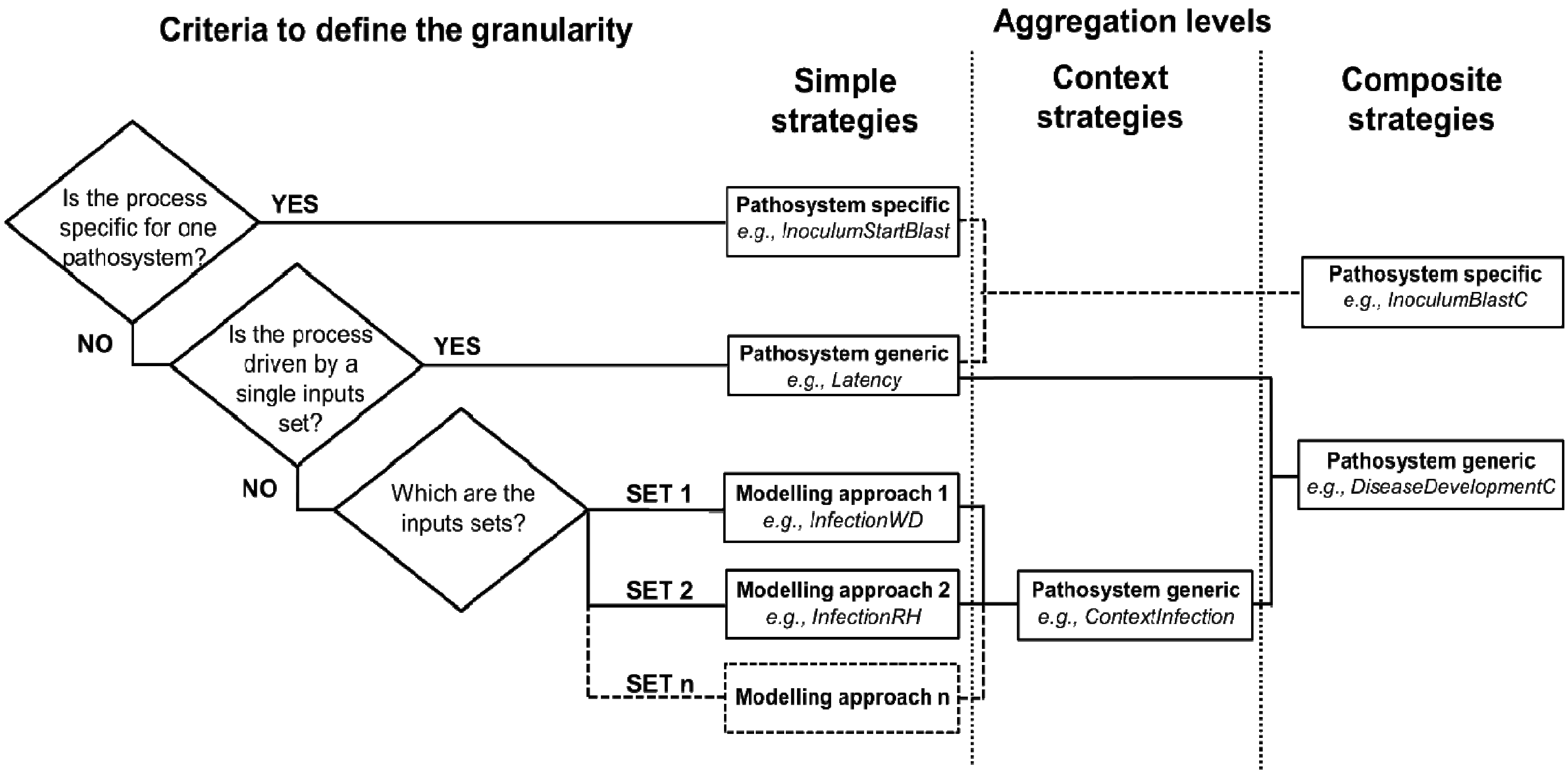
Outline

- The Diseases framework modules
- The software implementation
- Applications
- Conclusions

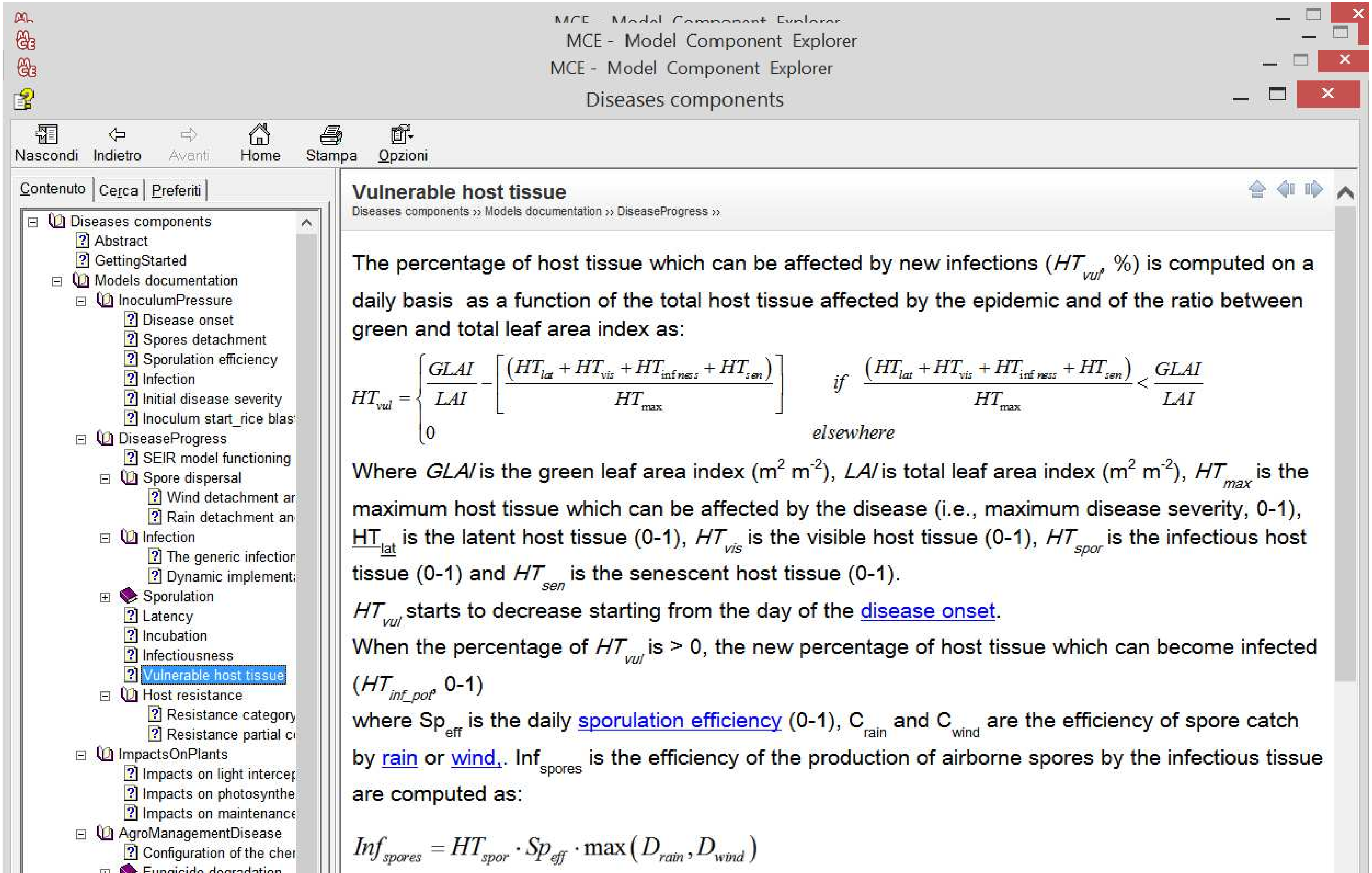
The software implementation

- The software implementation is based on four modules, each composed of two discrete units.
- Each module is implemented separating the description of the domain from the models; the library of models can be independently either extended or fully replaced, and also the library including the description of the domain can be extended.
- Models are implemented at fine granularity, referring to the description of the domain for inputs and outputs, whereas each model includes the definition of its own parameters.
- Models are meant to be composed, also to models from other components as crop libraries, to build modelling solutions which are also reusable in other platforms which are compatible at binary level (the platform is based on Microsoft .NET)

From knowledge to software units



The software implementation



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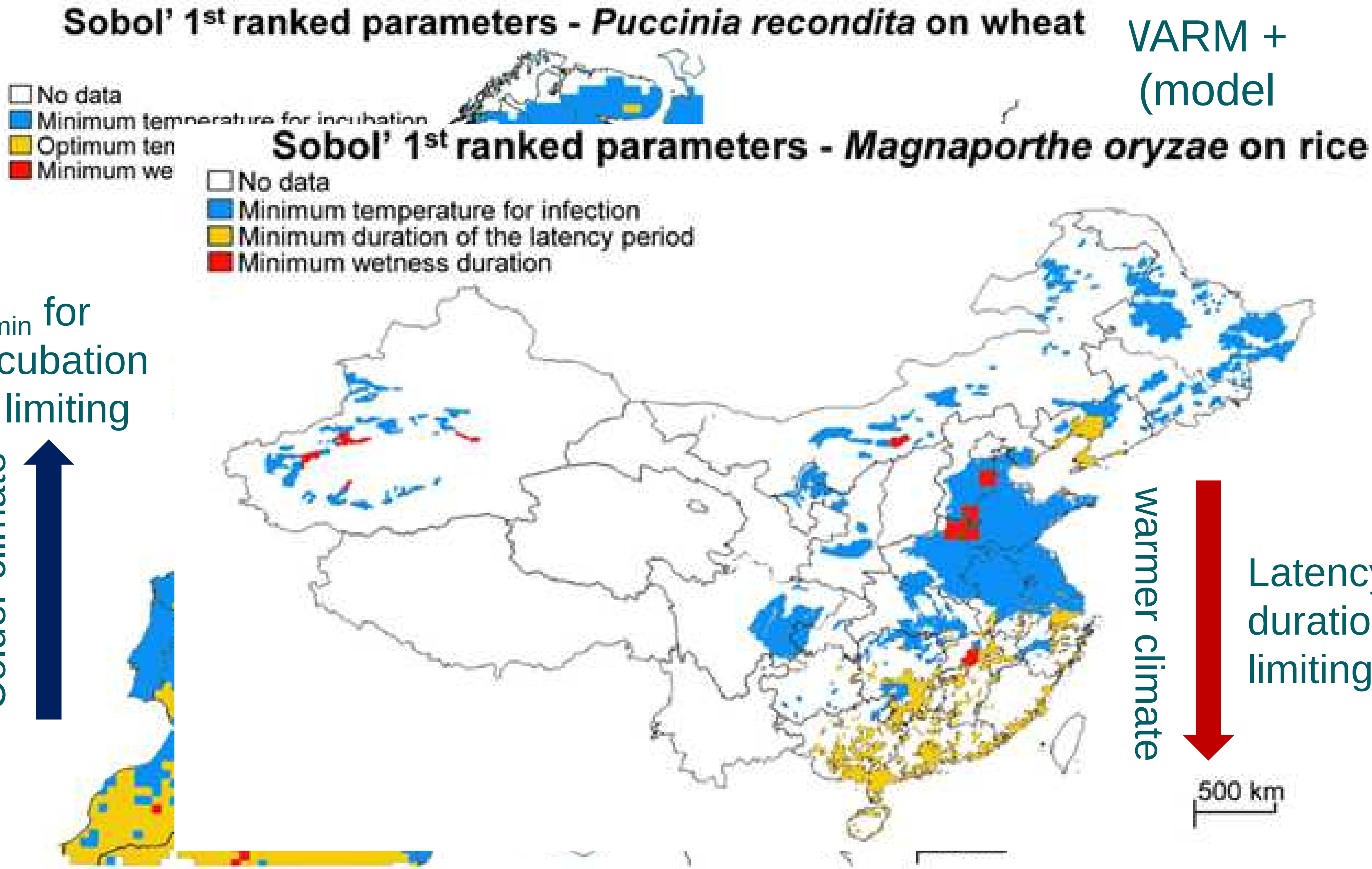
Application: sensitivity analysis



VARM + (model

T_{min} for incubation is limiting

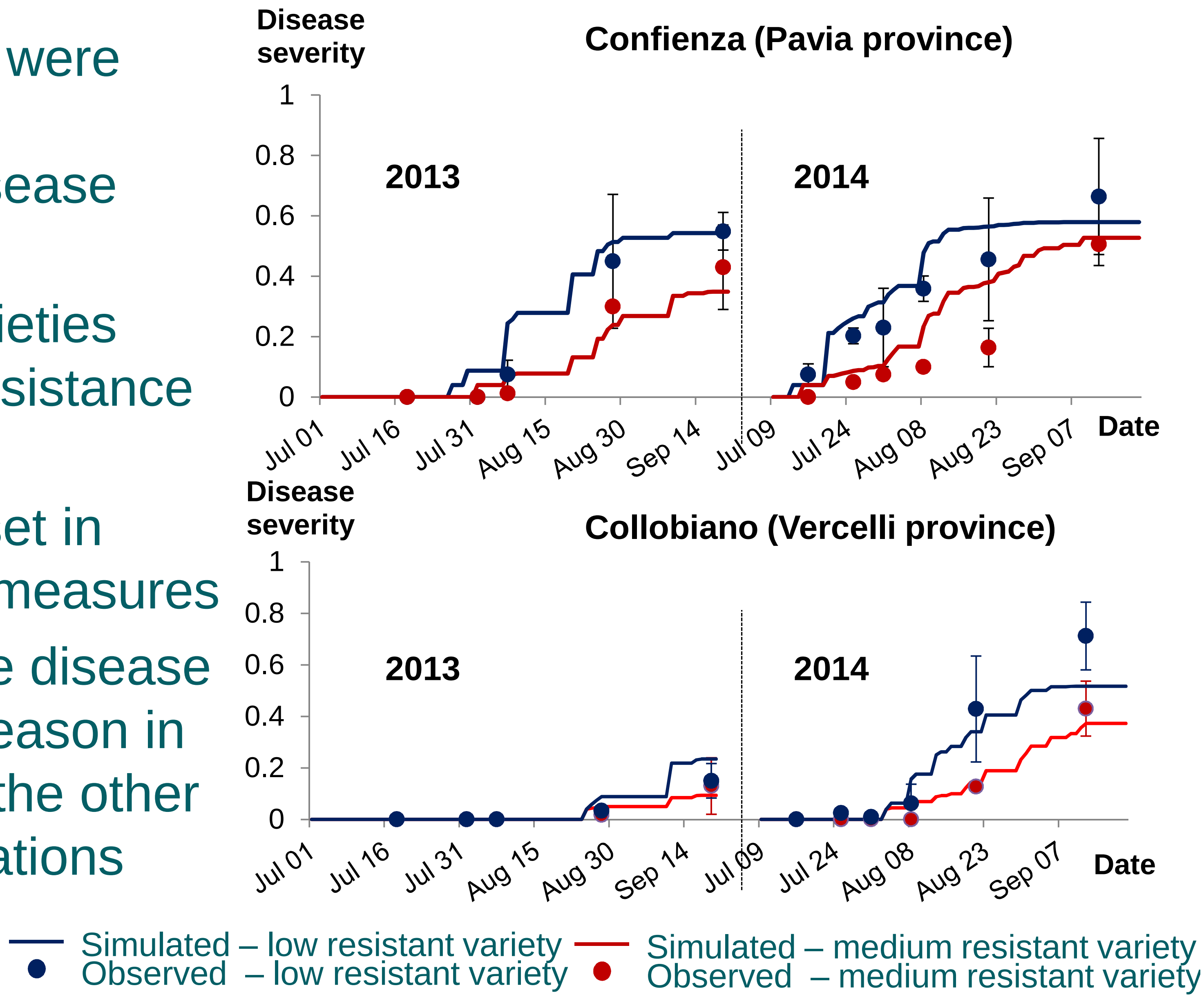
Colder climate

warmer climate

Latency duration is limiting

Application: disease severity

- The model outputs were compared to visual assessments of disease severity
- Two Italian rice varieties medium and low resistance to blast disease.
- Earlier disease onset in 2014 according to measures
- Lower impact of the disease in 2013 cropping season in Collobiano than in the other site × year combinations



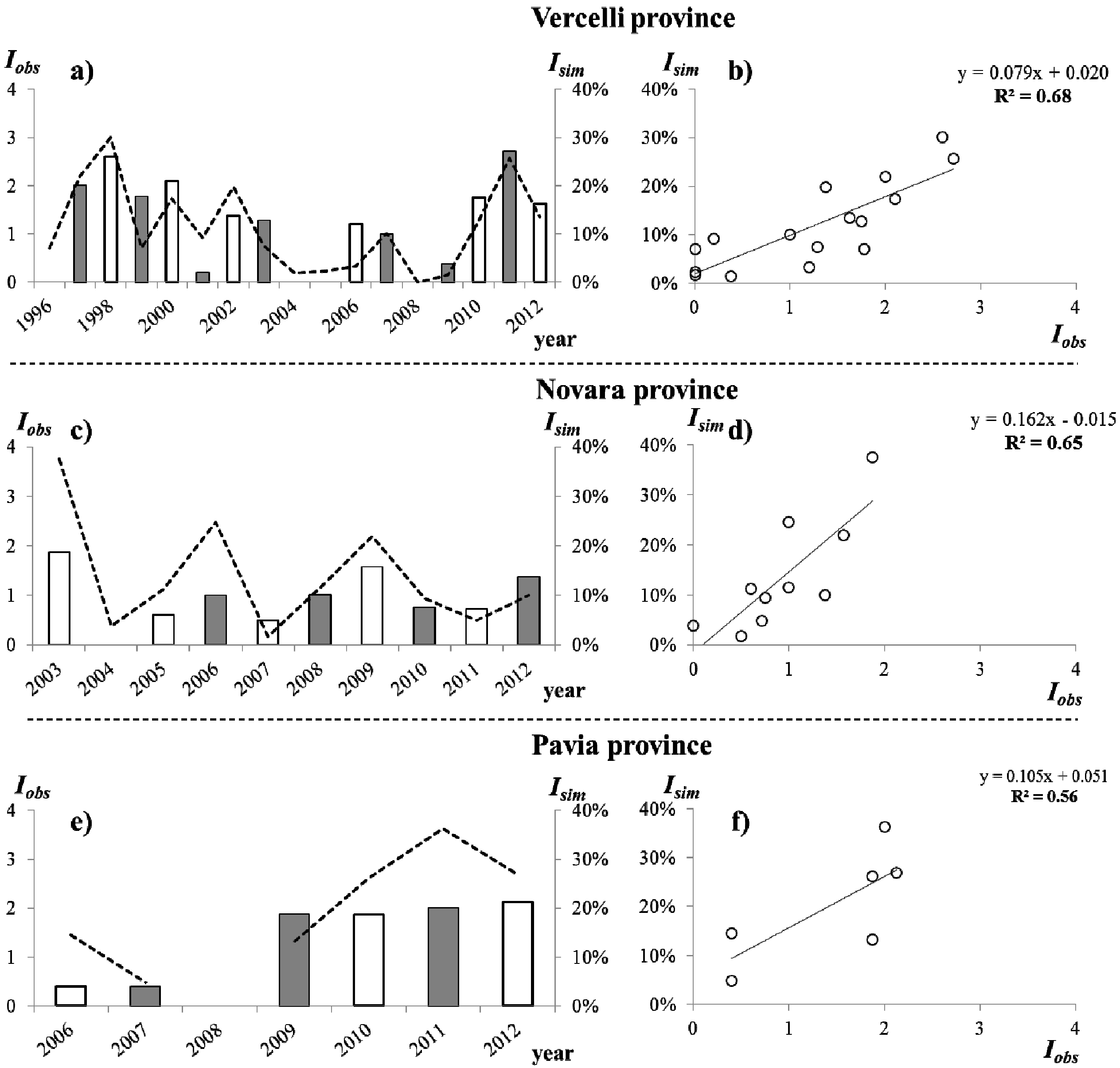
Application: rice blast

- Experimental field trials (paddy rice) carried out since 1996.
- Three sites in Northern Italy, around 40 rice varieties with different blast resistance levels.
- Visual assessments of the disease impact (i.e. leaf and panicle blast) on rice crop, ranked in a scale ranging from 0 (< 5 %) to 5 (> 60 %).

Leaf and panicle blast symptoms

Application: rice blast

- The modelling solution (WARM+Diseases) obtained similar performances for the calibration and evaluation datasets.
- Effective in reproducing the marked year-to-year fluctuations in the three sites.



Conclusions

- The framework proposed and the associated software infrastructure allows for a building-block process in which alternate and new models can be added to either extend or improve the simulation of diseases, and the impact on crops.

- Plant pathology modellers can use known crops models to develop specific cases, and hopefully crop modellers will be able to rely on a library of models for diseases simulation developed and tuned by specialists.

- The cooperation between plant pathology modellers and crop modellers is key to further develop and evaluate modelling capabilities, including the implementation of pathosystems of different diseases impacting simultaneously on crops.

Conclusions (2)

- The software architecture of this framework is not merely an application of technology, in fact, it directly impacts on knowledge sharing and building.

- As for other applications of the software architecture used, this framework does not present "the model"; instead it provides a way to build, compare, and use operationally modelling options.

The software development kit

http://goo.gl/mkatY9

https://en.wikipedia.org/wiki/BioMA