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MIMYCS – A framework for simulating maize kernels mycotoxin contamination in Europe

MIMYCS Project

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Abstract of the project MIMYCS

Mycotoxins are toxic compounds, produced by fungi and recognized as the main cause of chronic intoxications in the world. Maize is one of the crops subjected to the most critical mycotoxin problems throughout the world. Mycotoxin contamination in maize grain is the result of a complex plant pathosystem composed of maize plants, toxigenic fungi and insect borers. Warming of the climate system could have an important impact on the system, leading to mycotoxin contamination in grain maize and the potential effects are very difficult to foresee. The project MIMYCS has aimed at the development of a simulation model system to simulate at EU scale mycotoxin contamination in maize grain in different climatic, environmental and agro-management situations. The MIMYCS model system has been developed as composed by three main model components: i) MIMYCS.Maize, which integrates the crop model CropSyst and simulates maize phenological development and moisture in kernels during their development and maturation, ii) MIMYCS.Borers simulating two maize borers (Ostrinia nubilalis and Sesamia nonagrioides) phenological development and their damage to the ear, enhancing fungi growth and development, iii) MIMYCS.Fungi simulating fungi development and their interactions, using information received from Maize and the Borers modules. Finally, the MIMYCS simulation system, can quantify the risk of mycotoxin (aflatoxins, fumonisins, deoxynivalenol) contamination in maize grain. As a first application, MIMYCS has been used to predict and evaluate the effect of climate change on maize grain mycotoxin contamination in Europe. Future applications of MIMYCS will include its use as a decision support system to manage mycotoxin contamination during the field phase.

During the development of the project training activity have included: i) process-based modelling and biophysical model framework development, ii) basic concepts of insect pest population dynamics modelling iii) object-oriented and component-oriented programming with C#, iv) writing of scientific papers, v) project management, vi) agrometeorological analysis and crop forecast, vii) writing of project proposals.

Executive summary

Mycotoxins are toxic compounds, produced by fungi and recognized as the main cause of chronic intoxications in the world. Limitations set by the European Commission and by other nations of the world on the maximum levels of mycotoxins in cereal grain have had an important socio-economic impact on the global cereal market. Maize is one of the crops subjected to the most critical mycotoxin problems throughout the world. As a consequence, producing maize grain with acceptable mycotoxin content and simultaneously maintaining profitability has become more and more difficult, with important socio-economic consequences. Mycotoxin contamination in maize grain is the result of a complex plant pathosystem formed by maize plants, toxigenic fungi and insect borers. Meteorological and climate conditions play a key role in the contamination. As a consequence, warming of the climate system could have an important impact on the pathosystem and the potential effects are very difficult to foresee. The project MIMYCS has aimed at the development of a simulation model system to simulate the potential risk for contamination by aflatoxins, fumonisins, and deoxynivalenol, which are the three main toxin contaminating maize grain during the field phase.

The MIMYCS model has been implemented as a component of the framework BioMA, the modelling platform used at the European Commission Joint Research Centre. MIMYCS has been developed as composed by three main model software components. The model component MIMYCS.Maize includes the crop model CropSyst and simulates maize phenological development and maize grain moisture during development, maturation, and dry-down. The model component MIMYCS.Borers simulates the phenological development and damage activity of the two main maize borers (Ostrinia nubilalis and Sesamia nonagrioides) having a key role in mycotoxin contamination. The model component MIMYCS.Fungi simulates fungi development and their competitive interactions, and the consequent mycotoxin synthesis. Finally, the MIMYCS simulation system, quantifies the risk of mycotoxin contamination in maize grain, insect borers damage and fungi infection. The project has been developed in two years in collaboration with the Joint Research Centre of the European Commission. The project has also attracted the interest of a private company interested in the models of the MIMYCS framework: a collaboration agreement has been signed and work is on-going for implementing the MIMYCS models in the agro-management software system that this private company uses to assist their clients.

The main results of the project MIMYCS include:

- development of an original model for the simulation of moisture content in maize kernels during their development, maturation, and dry-down;
- implementation of a phenological model for the simulation of the European corn borer (Ostrinia nubilalis) and the Mediterranean corn borer (Sesamia nonagrioiodes);
- development of an original model for the simulation of fungi development, infection of maize grain, and mycotoxin synthesis;
- implementation of the models in independent, reusable, and extensible software components;
- Development of a framework of model integrating the three models components above, implemented as an independent model software component that was included in the BioMA platform of the European Commission
- Simulations at EU scale of maize borers phenological development under future climate scenarios
- Collaboration agreement with a private company interested in MIMYCS models.

Results of the project have been disseminated through poster and oral presentations in international scientific congresses and partially through peer reviewed scientific papers. Results will also be disseminated through web-pages in the web-site of the Joint Research Centre. Other papers to be submitted to ISI journals are in preparation.

A relevant part of the project has been dedicated to scientific and complementary training activities which have included:

- Process-based modelling and biophysical model development
- Insect pest population dynamics modelling

- Object oriented and component oriented programming with C#
- Writing of scientific papers
- Project management
- Agrometeorological analysis and crop forecast
- Writing of scientific reports to the European Commission
- ISO 9000 specifications for project management
- Writing of project poposals

The project has aimed at providing a first operational tool to simulate at EU scale mycotoxin contamination in maize grain in different climatic, environmental and agro-management situations. In this context, the development of MIMYCS will allow an easy re-use of it for performing simulations (i) to inform European policy makers involved in food and feed safety of the effects of European mycotoxin policies and help them to fix safe and, at the same time, feasible contamination limits, (ii) to assess about climate change scenario effects on the pathosystem and on future maize-based food and feed products safety, (iii) to assist maize producers in controlling mycotoxin contamination through agro-management and improving maize grain safety.

A Software Development Kit (SDK) is being prepared including software technical documentation, software examples, and development tools to help and enhance the implementation by third parties of the MIMYCS models. In this way, the models and the model framework developed during the MIMYCS project will be soon made available to the public through the Joint Research Centre web site.

Objectives of the Project

As a Marie Curie Project, MIMYCS included scientific and training objectives.

Scientific objectives included:

- Review of the main literature about the pathosystem leading to mycotoxin contamination in maize grain
- development of a model software component for the simulation of the phenological development and damage activity of the two most important maize insect borers: Ostrinia nubilalis (European corn borer (ECB), and Sesamia nonagrioides (Mediterranean corn borer);
- development of a model software component for the simulation of moisture dynamics in maize grain during kernel development, maturation, and dry-down;
- development of a model software component integrating a crop model for the phenological development of maize (CropSyst model) and the model for moisture simulation
- development of a model software component for the simulation of the infection cycle, growth and mycotoxin synthesis of the three most important toxigenic fungi in maize: Fusarium verticillioides, Fusarium graminearum, and Aspergillus flavus, and related mycotoxins (fumonisins, deoxynivalenol, aflatoxins)
- development of a model software component implementing a framework for simulating the system formed by maize, insect borers and fungi (model MIMYCS)
- calibration and validation of the model software components
- application of MIMYCS in spatialized simulation runs at the European scale to estimate the effect of climate change on mycotoxin contamination in maize grain in Europe

Training objectives included:

- increase knowledge on process-based modelling and biophysical model development
- acquiring new skills on object oriented and component oriented programming with C#
- increase knowledge on project management in an international environment
- acquiring new skills on writing scientific papers for ISI journals and international congresses
- acquiring new skills on agrometeorological analysis and crop forecast at the European level
- acquiring new skills on writing of scientific reports to the European Commission

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Section 1. BACKGROUND AND LITERATURE REVIEW

Abstract

Mycotoxins are toxic compounds, produced by fungi, recognized as the main cause of chronic intoxications. Maize is one of the crops subject to the most critical mycotoxin problems throughout the world. Limitations by many nations in the world about the maximum levels of mycotoxins in cereal have had an important economic impact on the global cereal market. Mycotoxin contamination in grain maize kernels is the result of the pathosystem formed by maize plant – insect borers – toxigenic fungi. This pathosystem is influenced by climatic conditions and by the fungi competitive relationships, which determine their prevalent geographical distribution. The main toxigenic fungi infecting maize ears are *Fusarium verticillioides* (producer of fumonisin toxins), *Fusarium graminearum* (producer of deoxynivalenol toxins), and *Aspergillus flavus* (producer of the aflatoxin toxins).

The main literature about the pathosystem and its components was reviewed in order to analyze the structure of the pathosystem and the biophysical processes involved in the development of each component and connecting the components themselves.

1.1. Background

Mycotoxins are toxic compounds, produced by fungi, recognized as the main cause of chronic intoxications. Maize, one of the principal crops grown for human food and livestock feed and occupying more than 8.5 million ha of cropland annually in Europe, is one of the crops subject to the most critical mycotoxin problems throughout the world. Limitations by the European Union (EU) (Comm. Reg. 1881/2006, Comm. Reg. 1126/2007, Comm. Recomm. 2006/576/EC) and by other nations of the world on the maximum levels of mycotoxins in cereal grain have had an important socio-economic impact on the global cereal market. In fact, aside from health risks, mycotoxin contamination can also reduce the price paid for crops or cause widescale market rejection (Wu 2006). These problems determine direct and indirect income losses that result in a dramatic reduction of farm numbers and more in general cause job losses. A study conducted by CAST (2003) estimated generated mean annual costs of € 445 millions in crop losses and € 13 millions in feed losses on maize and wheat in USA. As a consequence, producing maize grain with acceptable mycotoxin content and maintaining at the same time profitability has become more and more difficult, with important socio-economic consequences.

The most important mycotoxins in maize are aflatoxins, mainly by *Aspergillus flavus*, deoxynivalenol (DON, or vomitoxin) mainly by *Fusarium graminearum*, and fumonisins mainly by *Fusarium verticillioides*. Their development and mycotoxin synthesis is influenced by climatic conditions and by the fungi competitive relationships, which determine their prevalent geographical distribution: *A. flavus* (prevalent approximately in the range 26 - 35° latitude) takes competitive advantages under hot and dry climate conditions and can develop in substrates with relative low moisture content (from 16-17% wet basis), Fusarium spp. (F. verticillioides is prevalent in the range 37 - 46° lat,. and *F. graminearum* 45 - 50° lat.) are more competitive under cooler conditions and develop on substrates at higher moisture content (from 18-19% wet basis). Therefore, any of these species can develop and produce its mycotoxins even in those areas where they are usually not competitive, if conditions become favorable due to climate shifts as projected by many IPCC scenarios. Moreover, fungi infection is largely influenced by insect borers attack to the plants which can determine contaminations at rates 40 times higher than healthy ones. Thus, mycotoxin contamination in maize is the result of a complex pathosystem formed by Maize – Toxigenic fungi – Insect borers.

Warming of the climate system is unequivocal (IPCC 2007). These changes might have an important impact on the pathosystem. First, climate change could modify the actual competitive equilibrium between fungal species and as a consequence their prevalent geographical distribution: *A. flavus* is hypothesized to become a more significant danger in the south of Europe and *F. verticillioides* might became a danger also at higher latitude in Central Europe. This would result in significantly higher aflatoxin and fumonisin contaminations. Secondly, climate change is expected to modify the phenological development of maize insect borers (Porter 1995; Trnka et al. 2007). Thirdly, climate change will accelerate maize phenology and increase its water requirements, with higher risk of water stress which is recognized as one of the causes of high mycotoxin contaminations. Thus, the potential effects of future climate change on the pathosystem and on mycotoxin contamination are very difficult to foresee.

The objective of the project MIMYCS (Maize Infection and MYcotoxin Contamination Simulator) have been the development of a framework of models dealing with the complexity of the pathosystem aiming at providing a first operational tool to simulate at EU scale the system in different climatic, environmental and agro-management situations.

MIMYCS represents a useful tool for, (i) maize producers, to assist them in optimizing agro-management, (ii) policy makers, to better evaluate the extension and the distribution of mycotoxin contamination in Europe and to create safe but technically feasible mycotoxin standards in cereals, and (iii) for scientists, to study the pathosystem and the effects of climate change on it.

1.2. Literature Review

1.2.1. Toxigenic fungi life cycle and fungi interactions

The three main toxigenic fungi infecting maize kernels share a very similar pattern of life cycle. They can invade maize grain via three pathways: (i) systemic growth through seed transmission or in roots, stalks, or leaves; (ii) air- or splash-borne infection by conidia and spores produced on crop residues and tassels that infect ears through silks or insect-caused wounds; and (iii) insects as vectors of conidia. Among these pathways, systemic growth from contaminated seeds was demonstrated to be less harmful while the silk and insect routes are more relevant (Sutton 1982; Payne 1992; Munkvold et al. 1997; Oren et al. 2003). Once the fungi enter the ear, toxins can be synthesized and contaminate kernels that eventually enter the food or feed chain.

The main sources of inoculum in the field are maize residues incorporated into or covering the soil, infected seeds, and the soil itself. Overwintering structures are represented by fragment of hyphae, conidia, and sclerotia (Sutton 1982; Manzo 1984; Abbas et al. 2009). At the beginning of the growing season, when suitable environmental conditions arise, the overwintering structures germinate into mycelia that produce numerous conidiophores and release conidia into the air (Battilani et al. 2012). The production of new conidia (sporulation) depends on both temperature and substrate water availability. The amount of inoculum in a field and its dynamics are very variable and consequently very difficult to quantify (Sutton 1982; Battilani et al. 2004). Inoculum can be dispersed by wind, rain, and insects (Ooka and Kommedhal 1977; Sutton 1982; Fitt et al. 1989; Payne 1992; Cotten and Munkvold 1998; Miller 2001). Nevertheless, in the case of *A. flavus* it was shown that rain events and air relative humidity >75% significantly reduce or even preclude dispersion of inoculum (Abdalla 1988; Battilani et al. 2012). Dispersed spores land on silks where they can germinate and start silk infection. Germination is controlled by air relative humidity, temperature, and water availability on the substrate (Armolick and Dickson 1956; Sutton 1982; Marsh and Payne 1984; Munkvold and Desjardins 1997). The appearance of maize silking and its duration are very important in relation to the meteorological conditions throughout this stage when the silks are particularly susceptible to germination by the dispersed inoculum. Furthermore, silk development is a key factor in spore germination and in the successive fungus growth along the silks up to the kernels. Silk susceptibility to *F. graminearum* increases immediately after silk emergence, then decline. On the contrary, optimum condition for germination and growth of *F. verticillioides* and *A. flavus* are observed during silk browning and senescing (Marsh and Payne 1984; Reid et al. 1992; Stewart et al. 2002). After germination, germ tubes develop growing along the silks end enter kernels through the stylar canal (Duncan and Howard 2010). Duncan and Howard (2010) hypothesized also the passive movement of conidia along the surface of silks, perhaps via capillarity, as a possible mechanism for pathogen access to the infection court. Once the fungus enters the kernels, temperature and water activity are the main factors associated with fungi growth and fumonisin synthesis (Marin et al. 1999a; Samapundo et al. 2005).

Besides environmental factors, one factor that has a major impact on fungal growth is fungal interactions. In fact, maize grain is usually colonized by a mixture of spoilage fungi including the ones considered in this work, which compete for the same substrate. The understanding of the ecological conditions which determine the dominance of individual species over others is still limited. Nevertheless it is known that environmental factors such as water activity (aw) (Labuza and Altunakar 2007) and temperature, affect the interaction and competitiveness of toxigenic fungi. Marín et al. (1998) observed that *F. verticillioides* is dominant against many other species over a range of temperature and water activity 0.99 to 0.96. At these aw levels they observed that it can reduce the growth of *Aspergillus spp*. At lower aw levels it was less competitive and it did not affect *Aspergillus spp*. They also observed that *F. graminearum* at 15°C may be at a competitive advantage over *F. verticillioides* and that at aw<0.96 it loses its dominance. Giorni et al (2009) found that *A. flavus* was dominant over *F. verticillioides* at aw < 0.98. They also found that when mixed together, *A. flavus* optimum temperature for competition was 30°C while *F. verticillioides* was 20°C.

The three fungi considered share the same pattern of development but they are characterized by different responses to the environmental factors that influences their development, growth and mycotoxin synthesis. The specific responses to the environmental factor for each fungus considered

will be discussed in Section 3, when discussing parameterization of the model for simulating fungi development and mycotoxin synthesis.

1.2.2. Insect borers life cycle

The European corn borer (ECB – *Ostrinia nubilalis* Hb) and the Mediterranean corn borer (MCB – Sesamia nonagrioides) are two species of great concern for all the maize growers of Europe (ECB and MCB) and North America (ECB). Damage and yield losses result mainly from: leaf feeding, stalk tunneling and ear damage. Both ECB and MCB are lepidopteran and follow the same path of development (Figure 1): Their life cycle normally consists of an egg, larva, pupa, and an imago or adult.

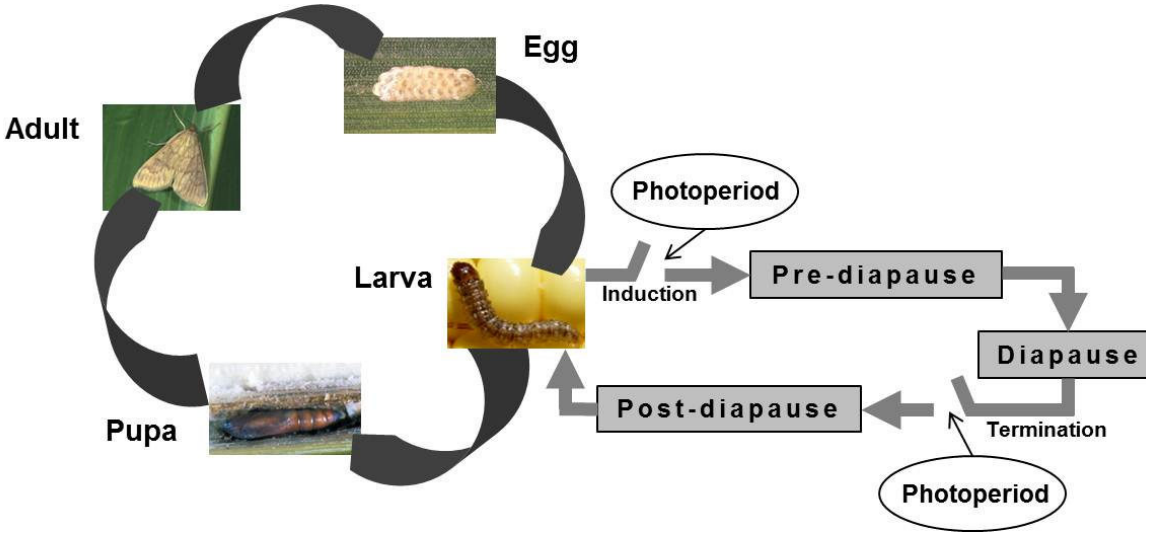


Figure 1. Development of *Ostrinia nubilalis* and *Sesamia nonagrioides*.

Each generation starts from the deposition of cohorts of eggs. The egg phase is followed by the larval phase which includes five instars in the case of *O. nubilalis* and up to seven-eight instars in the case of *S. nonagrioides*. After the last larval instar, larvae pupate. Adults eclose from pupae and depose new cohorts of eggs starting a new generation. The number of generations usually varies from one to three in the case of *S. nonagrioides* and from one to five in the case of *O. nubilalis*. Number of generations depends on climatic and genetic factors. The two lepidopteron overwinters in the larval stage, with pupation and emergence of adults in early spring. Diapause induction and termination are mainly controlled by length of scotophase (the dark phase of photoperiod) and temperature, the latter having a secondary importance.

Feeding activity of the larvae of the two lepidopteron is crucial in grain maize kernels contamination. Damaged ears can suffer fumonisin contamination at rates 40 times higher than healthy ones (Avantaggiato et al. 2003; Alma et al. 2005). In fact they facilitate the infection of toxigenic fungi in two ways: (i) larvae directly damage kernels by breaking the pericarp and giving the fungus a direct point of entry and (ii) the same larvae can act as vectors of the inoculum (endogenous or exogenous) and carry it directly inside the kernels (Sobek and Munkvold 1999; Cardwell et al. 2000). This is true especially for *F. verticillioides* and *A. flavus* while a clear relationship between borer damage and *F. graminearum* and deoxynivalenol accumulation has not been found (Sobek and Munkvold 1999; Windham et al. 1999; Cardwell et al. 2000). For this study, data and information about ECB damage severity on maize ears during maize development collected in Northern Italy (Alma et al. 2005, 2005; Blandino et al. 2006; Maiorano et al. 2009) were used for the development of the damage model. No other source of information about the dynamics of insect borer damage to ear was found in literature.

1.2.3. Moisture content of developing maize kernels

Maize grain moisture content during maturation and post-maturity dry-down is a very important factor influencing harvest and post-harvest management, and the technological and

safety of maize grain. In fact, moisture content influences harvest timing and the consequent drying process and drying costs, and the development of toxigenic fungi. Development of maize kernels in the field can be partitioned into three phases: i) lag phase, ii) grain filling and maturation drying, iii) and post-maturity dry-down (Figure 2).

The lag phase is a period of active cell division and differentiation. This phase is characterized by a rapid increase in water content with almost no dry matter accumulation. Following the lag phase is a period of rapid dry matter accumulation resulting from the deposition of seed reserves. As such, this stage is generally referred to as the effective grain filling period. As in the lag phase, water content continues to increase rapidly and eventually establishes the maximum volume of the seed (Borrás and Westgate 2006). Maximum water content occurs near mid grain filling. Thereafter, maize kernels undergo a net loss of water. Water loss from the kernels during effective grain filling is termed as "developmental" change in kernel water content as water is being displaced by translocated assimilates (Brooking 1990). During the third phase of development, seeds continue to lose water through translocation, reach 'physiological maturity' (maximum dry matter accumulation), and enter a quiescent state. Physiological maturity of maize is determined by the development of the so-called black layer or abscission layer. The development of this layer is determined by the collapse or crushing of the mass of cellular tissue in the placenta-chalazal layer. The placenta-chalazal layer is the conjunction between the basal endosperm cells and the phloem termini in pedicel and plays a critical role in post-phloem transport of water, sugars, and nutrients for developing seeds (Cochrane 2000; Kladnik et al. 2004).

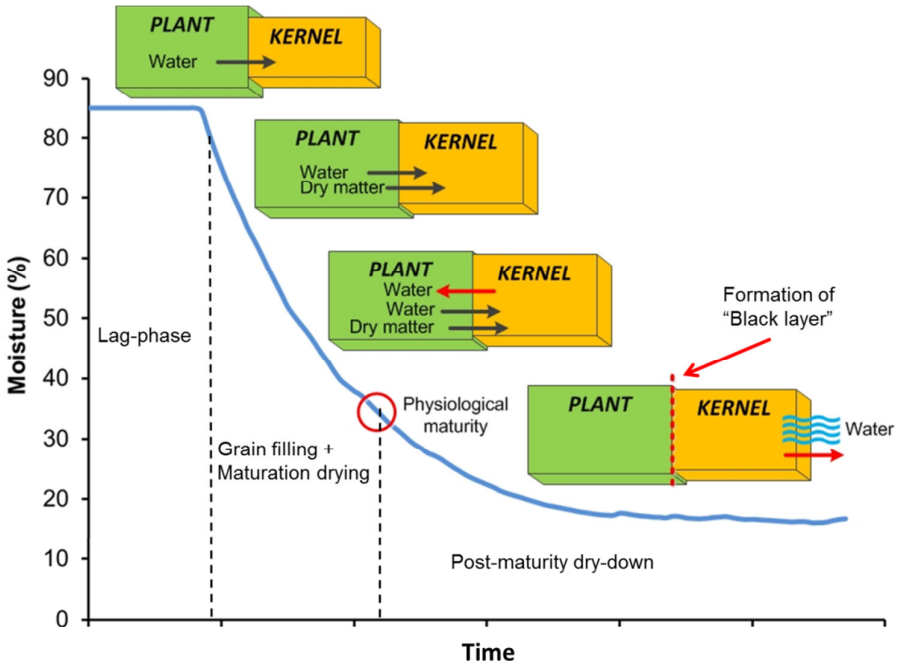


Figure 2. Dynamics of water content, dry matter accumulation and moisture content in developing maize kernels.

Once the placenta-chalazal layer crush or collapse, the kernel is isolated from the plant and the exchange of fluids is no longer between the plant and the kernel but between the kernel and the atmosphere and moisture loss occurs primarily by evaporative loss from the kernel itself. This phase is reached when the kernel water content is in a range included between 24-43% depending on the characteristics of the maize hybrid used (Nielsen 2011).

Section 2. CONCEPTUAL MODELS, MODELS DEVELOPMENT, IMPLEMENTATION

Abstract

On the basis of the results of the literature review a conceptual model and a relational diagram for each of the components of the pathosystem and for the pathosystem itself were formalized in order to represent the processes of the system that were modeled and the specific cause-effect relationships among variables, processes, and the components. Data-types of each domain were defined including states, rates, auxiliary, exogenous, external states, and external rates. Their definition allowed the development of the software interfaces for the software components. Based on the analysis of the 'best information available' the biophysical relationships were expressed with mathematical equations and algorithms. The conceptual models, mathematical equations, and algorithms were then used as a reference for development and implementation of model software components composed of discrete software units of fine granularity.

At the beginning of the section, a brief description of the platform BioMA used for running MIMYCS and of the tools used for software development is given.

2.1. Software Technology

The software engineering community routinely uses techniques that simplify the development of software applications. Using these techniques, modelers take advantage of important modern software engineering features such as ease of use and reuse, transparency, extensibility, robustness, ease of maintenance, standardization and cross-platform capabilities (Papajorgji et al. 2004). This can be achieved by implementing models using the component oriented programming paradigm, which is based on the concept of encapsulating the solution of a modelling problem in discrete, replaceable, interchangeable and interfaceable software units called components. As discussed by Donatelli and Rizzoli (2008), this type of software development technique has at least three major advantages. First, new models can be constructed by connecting existing component models of known quality with new component models. This increases the speed of development. Secondly, the predictive capabilities of different component models can be compared. Thirdly, frequently used generic simulation, presentation and analysis functionality, such as numerical integration and statistical ex-post analysis, can be developed once and readily shared by model developers. The platform BioMA is an example of such component based framework to simulate biophysical systems.

Developing a modelling solution based on fine granularity models has also the advantage of better understanding each model limits and its link to other models, both often confounded in monolithic implementations. Models are implemented as discrete models units of fine granularity, called Strategies. Simple Strategies can be composed to build CompositeStrategies; both can be used to build ContextStrategies in which the model to be used (a Strategy, simple or composite) can be used according to the state of the system. The fine granularity of model implementation allows an easier verification and maintenance, and allows composition using the same interface but keeping a solid and transparent underlying modelling structure. The clear separation between data and algorithms, the fine granularity, the attributes defined for each variable used make of this type of implementation a way to share modelling knowledge via operational software units. MIMYCS will follow this pattern of development, consisting in a set of independent components linked in a BioMA modelling solution.

2.1.1. The BioMA platform

MIMYCS has been implemented as a component of the platform BioMA (http://bioma.jrc.ec.europa.eu/). BioMA (Biophysical Models Applications) is the modelling platform used at JRC-AGRI4CAST for impact studies on agriculture related to weather and agricultural management. The main components of the framework are shown in Figure 3. BioMA is developed using the component-oriented paradigm both for model and utility components. Model implemented in discrete components can be either linked or used alone to build modelling solutions that is model chains assembled to address a specific modelling problem. MIMYCS has been implemented as a modelling solution using the crop phenology model CropSyst available already in the framework, and implementing new models for the MAIZE, BORERS, and FUNGI modules. All model components share the same architecture which provides many features that facilitate their re-use, from explicit ontology of the interfaces to the capability of extend them autonomously (Donatelli and Rizzoli 2008). Examples of the model components available are CropML (implementing the crop/cropping system models WARM, Wofost, CropSyst), the Diseases component (implementing a generic framework to simulate air-borne diseases) or the CLIMA weather generator component.

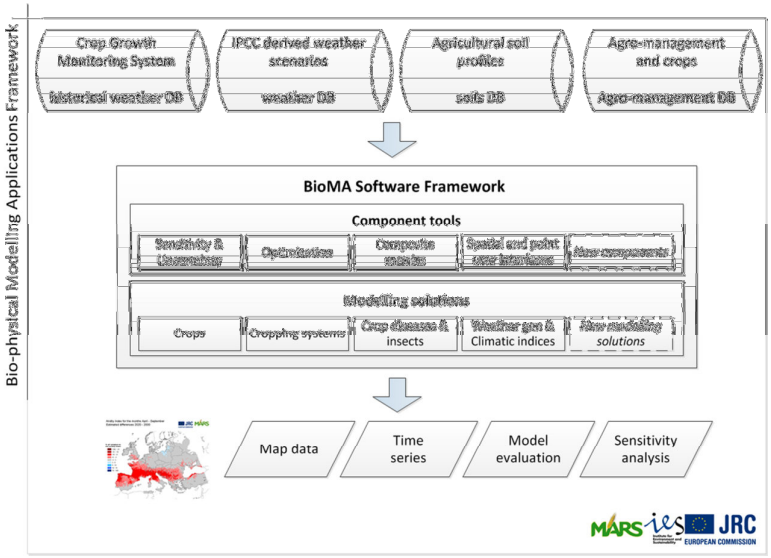


Figure 3. Components and outputs of the BioMA framework. New models, modelling solutions, and tools can be added (not all modelling solutions currently available are shown).

Modelling solutions in BioMA often use the AgroManagement component, which allows building rules to trigger agro-management actions during the simulation based on states of the system. Several tool components will be also soon available to assist in model development and use, such as the sensitivity analysis (LUISA), the calibration (Optimizer), and the model evaluation (IMMA).

2.1.2. Software development tool 1: the Domain Class Coder (DCC)

The *Domain Classes Classes Coder* (DCC) (http://agsys.cra-cin.it/tools/dcc/help/) is a Windows application to generate C# (.NET 2.0 platform) code to be used as domain classes containing values and attributes for each variable used to model a given domain. Attributes are set via the type VarInfo, which implements a set of attributes to describe a variable: Name, Description, MaxValue, MinValue, DefaultValue, Units, Type, URL. The application targets at facilitating the labour consuming process of coding domain classes, in perspective using information retrieved via a web application from an online knowledge base linked to an ontology. A model component using domain classes encapsulates its relevant ontology. The set of attributes allows identifying univocally all the concepts (variables in component terms) used in a component. Such values can be used for general documentation, and for testing pre- and post-conditions, according to the design-by-contract approach. The content of domain classes can be either extracted from a centralized repository (via a web application which allows downloading an XML file), or defined in an Excel file and exported as a tab delimited file. Such files can be processed by DCC to produce the value and VarInfo classes code. If input data are provided via a tab delimited file, they can also be exported as an XLM file inclusive of schema. Such XML file can be used as a definition file for the Model Parameter Editor (MPE). The code generated includes the implementation of the ICloneable interface, providing the capability of creating a deep copy of the types listed. One option of generation allows generating a parameter domain class, which includes the code to load parameter values from an XML file (via MPE). This option allows, also as an option, loading via reflection on a dll parameters definitions from a model class (implementing *CRA.Core.Preconditions.IStrategy*). The component can be used both for tests of pre- and post-conditions in other components, and in applications, for field validation in user interface forms. If DCC is installed from the installation URL, every time the program is launched a check for updates is made.

2.1.3. Software development tool 2: the Model Parameter Editor (MPE)

Developing and maintaining a simulation system implies, among other things, that the parameters used can change. Composite models are made of simpler model, which can be often interchanged by alternative formulations. This means that the development and management of a simulation system may require the ability to deal with the fact that the number and type of the

parameters of the composite model may change, each time a sub model is substituted. If the system is made of interchangeable components, the need of dealing with different sets of parameters is a inherent feature of the system; an alternate component may model the same domain variables, but its approaches may demand for different, model specific, parameters. The need of changing parameters used has a primary impact on the graphical user interfaces developed for the system: such user interfaces must be easily maintenable, and they must present the same look and feel to the user. Moreover, the capability of performing a check of the correctness of parameter value should be available for each set of parameters. A parameter editor with these features must allow for changing the parameters to be edited without changing the code, hence without a need for re-compilation of the editor. The *Model Parameters Editor* (MPE) (http://agsys.cra-cin.it/tools/mpe/help/) is an application which allows generating a dedicated user interface for each parameter definition made available. It can group interfaces in different tabs either according to a user criterion, or according to the different model components which originate the parameters definition. The application allows either selecting parameters definitions, or it loads automatically parameters definitions from a folder of choice. A separate application is provided to build parameters definitions as an XML file. Files with parameters values can be saved/loaded from XML files (one per parameter definition); other drivers to save/load parameters can be added. A test of values adequacy (values within a range provided in their definition) is performed when saving values. Files containing parameter values can be merged (within the same definition). Code snippetts to access parameter values into model components are provided in C# and Java. MPE is an application running under Windows and requiring the Microsoft .NET 2.0 framework.

2.1.4. Software development tool 3: the Model Component Explorer (MCE)

The *Model Component Explorer* (MCE) (http://agsys.cra-cin.it/tools/mce/help/) is a Window application to visualize the interfaces and the ontology of components developed according to the design proposed by Donatelli and Rizzoli (2008). The design uses domain classes to make the component interface semantically rich; MCE allows identifying domain classes, the attributes of each variable, and the signature of each interface model. Also, for each model implemented, MCE allows identifying inputs, parameters (if any), outputs, and associated models (if any). Finally, MCE shows the dependencies of each component. MCE also allows exporting the information above as Xml files which can used to populate an ontology browser.

2.2. The MIMYCS.Maize model component

2.2.1. MIMYCS.Maize conceptual model

Figure 4 shows the conceptual model of the MIMYCS.Maize simulation model. Soon after the flowering stage, maize kernel starts development.

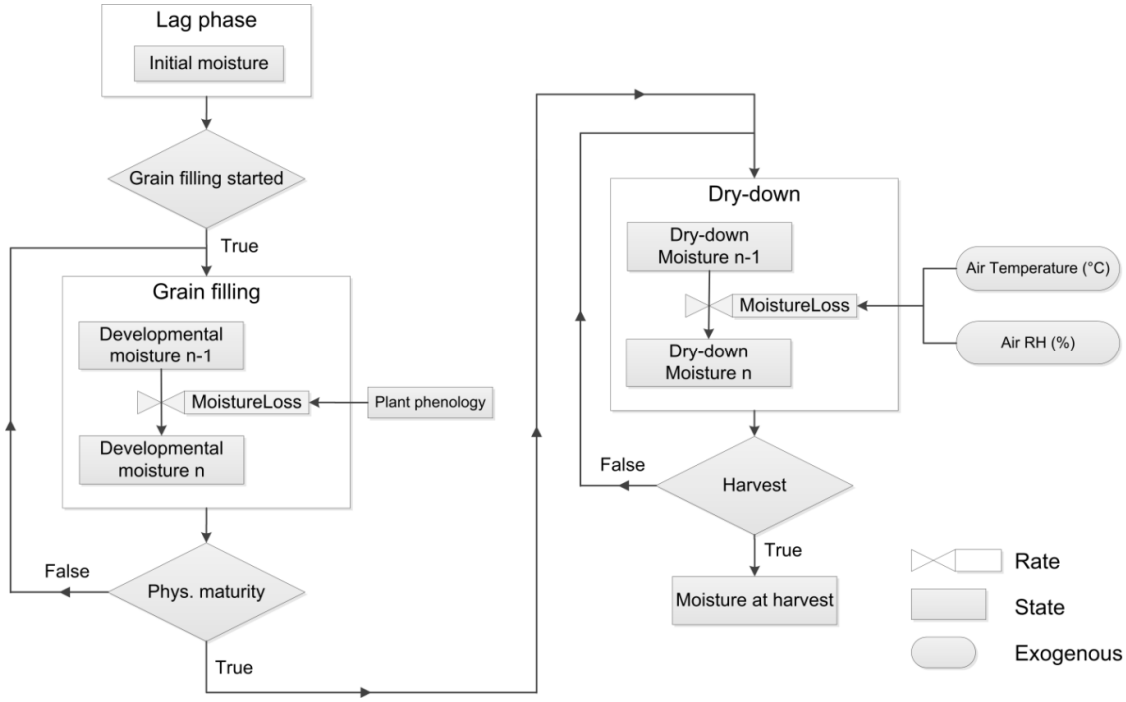


Figure 4. Conceptual model of the model MIMYCS.Maize for the simulation of maize kernel moisture during development and dry-down

During the lag phase it is assumed that moisture content is constant. After the starting of grain filling kernel moisture starts to decrease according to a negative rate of moisture loss based on maize phenological development. After physiological maturity is reached, dry-down moisture loss starts and actual moisture is calculated according to a moisture loss rate based on air temperature and relative humidity. When maize crop is harvested, model stops giving the moisture at harvest.

2.2.2. MIMYCS.Maize model development

The MIMYCS.Maize model integrates the crop model CropSyst (Stockle et al. 2003) for the simulation of the phenological development of maize.

According to Gambín et al. (2007) the lag phase was considered a constant and it was estimated that 290 degree-days (as calculated by CropSyst) from flowering are needed to complete the lag phase and to start the developmental moisture loss. Moisture (%) during lag phase was also considered constant and estimated equal to 85% (Brooking 1990; Gambín et al. 2007).

Following the example of Ma and Dwyer (2012) the rate of moisture loss during grain filling (i.e. developmental moisture) was considered proportional to moisture content itself and modeled as an exponential decay process whose general equation is:

$$Y(X) = Y_0 e^{-kX} \quad (1)$$

where Y_0 is the initial value of the function, k is a parameter, an X is time variable.

Ma and Dwyer (2012) used the number of days after silking for the variable X, and used k as a fitting parameter. Differently from them, in MIMYCS.Maize degree-day since the end of the lag phase was used as the time variable. As a consequence, equation 1 can expressed as:

$$M(t) = M_0 e^{-kt} \tag{2}$$

where M(t) is moisture (%) at time t (degree-days – DD) and M_0 is moisture (%) at the end of the lag phase (i.e. 85%, see above). Since this model is used for the simulation of moisture content from the lag phase to physiological maturity, assuming that degree-days from flowering to physiological maturity are known (they are used as parameters for the CropSyst model), and that moisture content at physiological maturity is also known (parameters to MIMYCS.Maize), equation 2 can be solved for obtaining k:

$$M(t_{fis}) = M_0 e^{(-kt_{fis})} \tag{3}$$

where $M(t_{fis})$ is the moisture content at physiological maturity which is reached at t_{fis} (DD).

Taking the natural logarithm of both sides:

$$\ln\left(\frac{M(t_{fis})}{M_0}\right) = -kt_{fis} \tag{4}$$

and rearranging for k:

$$k = -\frac{\ln\left(\frac{M(t_{fis})}{M_0}\right)}{t_{fis}} \tag{5}$$

In this way constant k is calculated through parameters to the model with a clear ecological meaning, and not as a fitting parameter as done by Ma and Dwyer (2012).

Once physiological maturity is reached, the model simulating moisture loss during kernel development stops and the one simulating moisture during dry-down is started. The rate of moisture loss during dry-down was modeled according to the findings of Henderson and Perry (1966) who reported that the declining water content of grains is inversely proportional to the water to be removed, given by the difference between the actual moisture and the equilibrium moisture content. As an equation:

$$\frac{dM}{dt} = -k(M - M_e) \tag{6}$$

where M is the water content at time t (% dry basis), M_e is the equilibrium water content (% dry basis), and k is a proportionality constant.

The equilibrium moisture content of a material is defined as the moisture content at which there is no exchange of water between the material and its surrounding under a given vapor pressure (Earle and Earle 2004). In this condition there is no exchange of water between the material and its surrounding. Henderson (1952) defined the equilibrium moisture content (% dry basis) by the following empirical equation

$$1 - RH = e^{-c(T+k)Me^{n}} \quad (7)$$

rearranged for M_e:

$$M_e = \left(\frac{\ln(1-RH)}{-c(T+k)}\right)^{\frac{1}{n}} \quad (8)$$

where *RH* is the air relative humidity (expressed as a proportion), *T* is air temperature (°C), and *c*, *k* , *n* are constants specific for the considered material. In the case of maize grain, the values found by Lee and Chung (1995) were used to parameterize MIMYCS.Maize:

- c = 49.81 (in MIMYCS.Maize this is named *ModifiedHendersonC*)
- k = 8.6541×10^{-5} (in MIMYCS.Maize this is named *ModifiedHendersonA*)
- n = 1.8634 (in MIMYCS.Maize this is named *ModifiedHendersonB*)

MIMYCS.Maize includes a model for the calculation of water activity from kernel moisture. For this first version of MIMYCS.Maize, the GAB model (Labuza and Altunakar 2007) was used and parameterized according to Maiorano et al. (2009). The use of the model calculating aw is functional to the use of MIMYCS.Maize for simulating fungal growth and development. In the case of using MIMYCS.Maize as a stand-alone model component to be used e.g. integrated in a crop model, the model component for water activity can be excluded.

Inputs required by the MIMYCS.Maize software component are: degree-days from flowering, hourly air temperature (°C), hourly relative humidity (%).

Outputs are: moisture dry basis (%), moisture wet basis (%), and water activity (aw).

In Table 1 parameters and constants name, and description, and the values used for simulating maize kernel moisture in MIMYCS.Maize are shown.

Parameter/constant name	Value	Description
ModifiedHendersonA	$8.6541*10^{-5}$	Parameter k of equation (7)
ModifiedHendersonB	1.8634	Parameter n of equation (7)
ModifiedHendersonC	49.81	Parameter c of equation (7)
LagPhaseDuration	290	Duration of lag phase (DD)
MoistureAtTheBeginningOfKernelFormation	85	Moisture (%) at the beginning of kernel formation
MoistureAtPhysiologicalMaturity	(*)	Moisture (%) at physiological maturity
GAB parameter C[a]	200	Parameters for the estimation of water activity using the GAB model
GAB parameter K[a]	0.9149	
GAB parameter M0[a]	0.0448	

Table 1. Parameter and constant name, value, and description of the model MIMYCS.Maize.

2.2.3. MIMYCS.Maize software component diagram

Figure 5 shows a diagram showing the fine granularity of and the relationships between the software components developed for the model MIMYCS.Maize. The software component can be implemented independently from the MIMYCS framework for simulating maize kernel moisture during maturation.

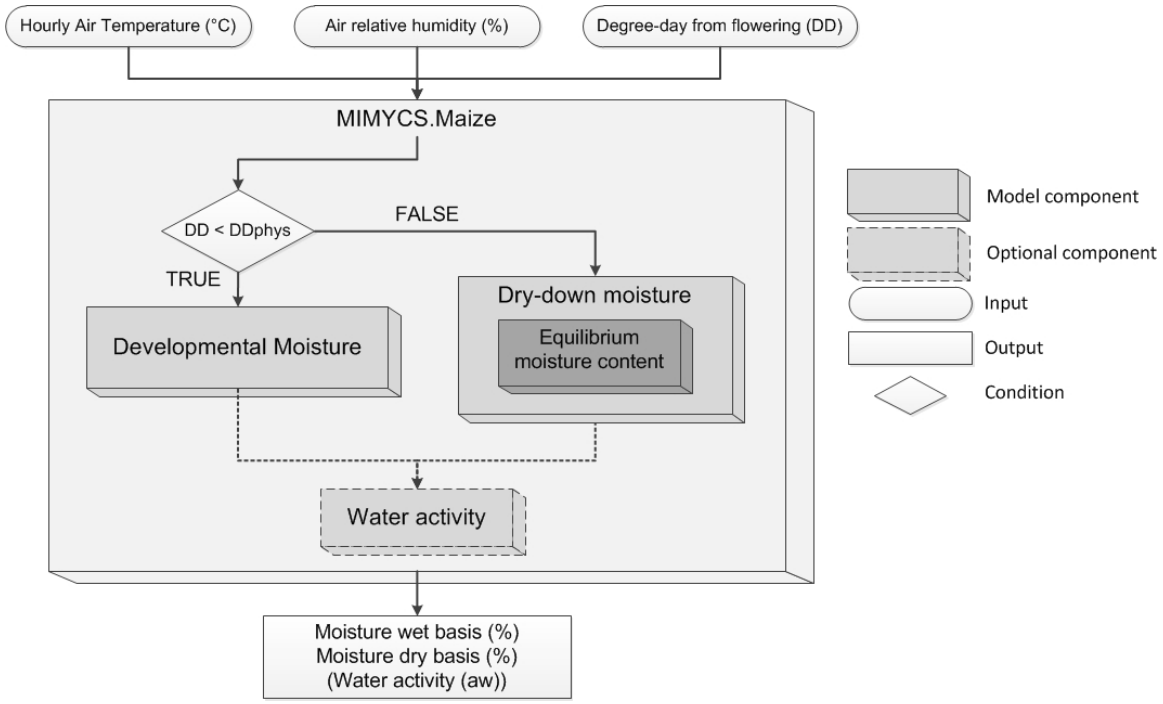


Figure 5. MIMYCS.Maize model components and sub-components. DD = actual degree-days from flowering. DDphys = Degree-days required to reach physiological maturity

2.2.4. MIMYCS.Maize testing

MIMYCS.Maize was tested using data of maize grain moisture during maturation and post maturity dry-down from literature (Source: Borras 2003; Gambín et al. 2007 – data from Argentina) and from field samples taken from the Piemonte region in Northern Italy.

The model was evaluated by evaluating its accuracy using RMSE (dimensionless, 0 to+∞, optimum=0; Fox 1981), modelling efficiency (EF, dimensionless, −∞ to 1, optimum =1; where a negative value indicates that the average of observations is a better predictor than the model; Nash and Sutcliffe 1970), and the coefficient of residual mass (CRM, dimensionless, −∞ to+∞, optimum=0, where a positive value indicates model underestimation, and negative indicates model overestimation; Loague and Green 1991). Results of simulations showed that the model was accurate in the explored conditions, reproducing correctly the loss of moisture during maturation and dry-down (Figure 6, Figure 7, Figure 8, Figure 9).

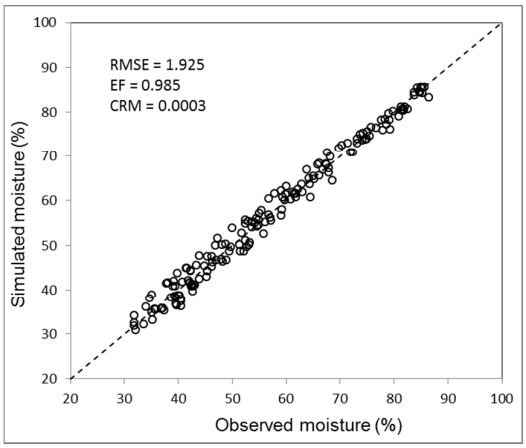


Figure 6. Observed vs simulated moisture content of samples collected during developmental moisture in Argentina (data from Borras 2003; Gambín et al. 2007)

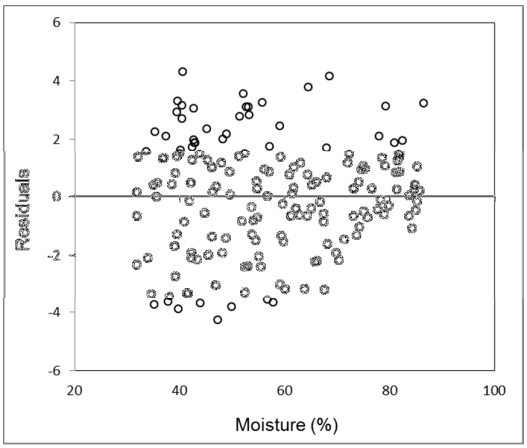


Figure 7. Observed vs simulated moisture content residual plot. Same dataset of Figure 6

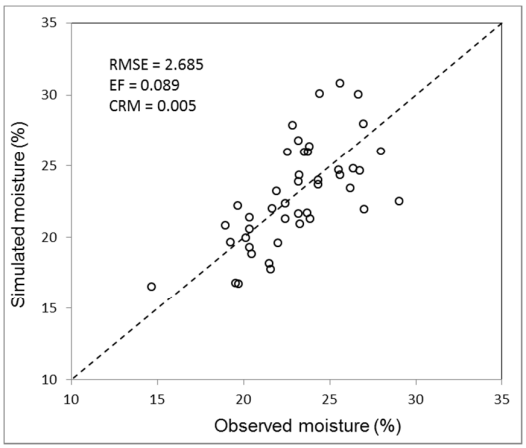


Figure 8. Observed vs simulated moisture content (%) of samples collected during dry-down, after the reaching of physiological maturity. Samples collected at two locations in Northern Italy during 2 years (2006 and 2007).

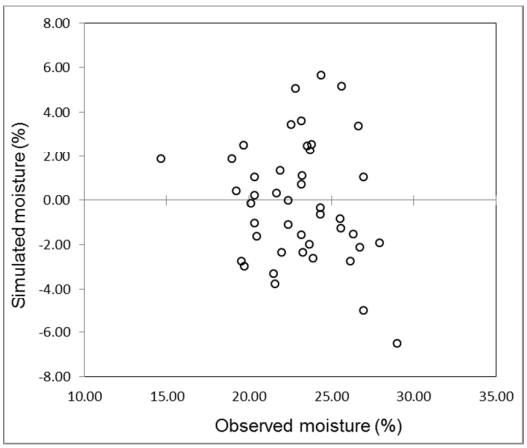


Figure 9. Observed vs simulated moisture content (%) residual plot. Same dataset of Figure 8.

The model will be further tested with a set of more homogeneous data from many samples collected in different locations in the Po Valley in Northern Italy during 3 years. These data will be made available by the company Syngenta Seeds which is interested in the model components of the project MIMYCS and with which a collaboration agreement was signed (see Section 5, Paragraph 5.1.4).

2.3. The MIMYCS.Borers model component

2.3.1. MIMYCS.Borers conceptual model

The phenological development of the European corn borer (ECB – *Ostrinia nubilalis*) and of the Mediterranean corn borer (MCB – *Sesamia nonagrioides*) has been schematized in a generic lepidopteran insect phenology diagram used to develop the phenological model and to implement the MIMYCS.Borers software component (Figure 10). The phenology diagram includes, for each phenological stage, the developmental event that triggers the following stage.

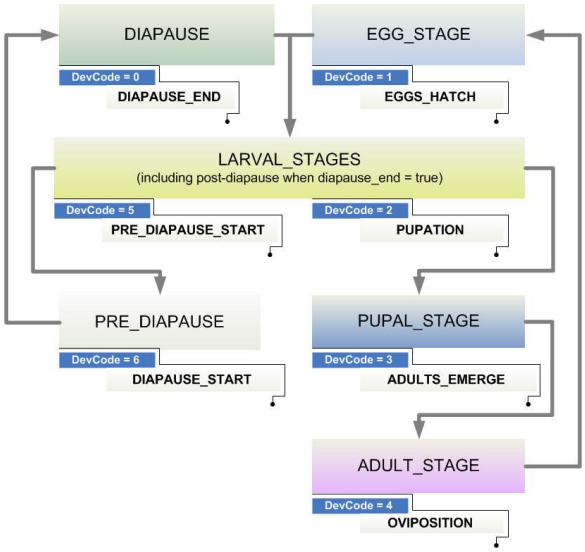


Figure 10. Generic lepidopteran phenology diagram. Phenological stages and developmental events that trigger beginning of new stages are indicated. Each stage is characterized by a developmental code (DevCode)

The Larval stage has been divided into two sub-stages: young larvae (up to the second larval instar) and mature larvae (from the third instar). This has been done in order to better simulate the damage provoked by the larvae to the ear: in fact it is known from literature that the damage is mainly provoked by the mature larvae.

2.3.2. MIMYCS.Borers model development

Modeling of phenological development

The Borers phenological model is based on a developmental model and on a degree-day model. The developmental model is a generic degree-day compartmental system model proposed by Brown (1982) in which the number of individuals in each life stage at a given time is given by:

$$\frac{dN_i}{dt} = XN_{i-1} - YN_i \tag{9}$$

where

$$X = \frac{t - B_i}{E_{i-1} - B_i}, \quad if \quad B_i \le t \le E_{i-1}$$
$$X = 0, \quad if \quad t < B_i \ or \ t > E_{i-1}$$

And

$$Y = \frac{t - B_{i+1}}{E_i - B_{i+1}}, \quad if \quad B_{i+1} \leq t \leq E_i$$
$$Y = 0, \quad if \quad t < B_{i+1} \ or \ t > E_i$$

where *N* is the number of individuals in life stage *i* at time *t* (in degree days), *B* is the degree day accumulation at which that stage begins to appear and *E* is the degree day accumulation for terminating that life stage. In the case of the first life stage *N0* (which is 'overwintering larvae' in the case of *O. nubilalis* and *S. nonagrioides*) the equation is:

$$\frac{dN_0}{dt} = \frac{-(t - B_i)}{E_0 - B_i}, \quad t \geq B_i \tag{10}$$

This approach allows maintaining constant the total number of individuals which are flowing from a life phase to another. According to Brown (1982), the initial number of overwintering larvae, *N0*, is an arbitrary value for phenological forecasting since the model is not intended for use as a density forecasting tool. For predictive purpose, stage-specific output is converted into % of peak occurrence (Brown 1982).

The degree-day model to determine the initiation (*Bi*) and termination (*Ei*) of each developmental stage is a physiologically based degree-day model based on the beta-function developed by Yin et al (1995), in this work adapted to degree-day calculation:

$$DD(h) = D_{max}\left(\left(\frac{T(h) - T_{min}}{T_{opt} - T_{min}}\right)\left(\frac{T_{max} - T(h)}{T_{max} - T_{opt}}\right)^{\left(\frac{T_{max} - T_{opt}}{T_{opt} - T_{min}}\right)}\right)^{c} \tag{11}$$

where, *D(h)* is the degree-days accumulated during the hour *h*, *Tmin* is the minimum extreme temperature for insect development, *Tmax* is the maximum extreme temperature for insect development, *Topt* is the optimum temperature for insect development, *T(h)* is the hourly air temperature, *Dmax* is the maximum degree-days that can be accumulated at the optimum temperature *Topt*, and *c* is the shape parameter. In comparison to other beta-functions (Logan et al. 1976), this equation has the advantage that all parameters except c are biologically meaningful.

In order to be used at an hourly time step, at each time step the hourly degree-days are multiplied for 1/24 and then accumulated. The date to begin accumulating degree-days (biofix) has been fixed according to the information found in literature about *O. nubilalis* and *S. nonagrioides* diapause termination. The specific parameters for *O. nubilalis* and *S. nonagrioides* were derived from literature and are shown in Table 2, showing the degree-days for the beginning (*Bi*) and the ending (*Ei*) of each stage and different generations, and in Table 3, showing the developmental and diapause termination parameters.

The date to begin accumulating degree-days (i.e. biofix) has been fixed according to the information found in literature about ECB diapause termination. According to the studies of Skopik and Bowen (1976), diapause termination starts after 4 days with scotophase < 10 hours. In the Piemonte region, scotophase is <10 hours at April, 8. Furthermore, according to Trnka et al. (2007), if during the period up to the stage of the first flight initiation (flight of the overwintering generation), temperature drops below a certain temperature for 3 consecutive days, the thermal time calculation is resumed from the beginning of the cycle. Trnka et al. fixed this limit to 0.2°C. In this work, a more generic limit of 0°C has been preferred.

Parameter Name	Generation													
	Wintering		1		2		3		4		5		6	
	Bi	Ei	Bi	Ei	Bi	Ei	Bi	Ei	Bi	Ei	Bi	Ei	Bi	Ei
Ostrinia nubilalis														
Eggs	-	-	339	550	967	1311	1571	1952	2176	2593	2780	3234	3384	3876
Young Larvae	-	-	417	672	1033	1439	1638	2080	2242	2721	2847	3362	3451	4003
Mature Larvae	-	280	633	900	1189	1648	1793	2289	2398	2930	3002	3571	3607	4212
Pupae	139	311	800	961	1387	1718	1991	2359	2596	3000	3200	3641	3804	4282
Adults	233	422	900	1078	1457	1788	2061	2429	2666	3070	3270	3711	3874	4352
Adult Flight	306	500	922	1217	1527	1858	2131	2499	2736	3140	3340	3781	3944	4422
Sesamia nonagrioides														
Eggs	-	-	236	471	761	995	1319	1554	1912	2147				
Young Larvae	-	-	282	517	806	1041	1365	1600	1958	2192				
Mature Larvae	-	166	491	726	1015	1250	1573	1808	2166	2401				
Pupae	49	284	540	775	1064	1299	1623	1857	2215	2450				
Adults	121	320	629	934	1170	1414	1746	1990	2356	2600				
Adult Flight	194	356	718	1092	1276	1530	1869	2122	2496	2750				

Table 2. Degree-days for the beginning (Bi) and the ending (Ei) of the life stages of *O. nubilalis* and *S. nonagrioides* for different generations.

Parameter name	Values		Description
	ECB	*MCB*	
Tmin	8.2	5.70	Minimum temperature for development
Topt	34.9	30.68	Optimum temperature for development
Tmax	41	40	Maximum temperature for development
Shape parameter	1.47	2.15	Shape parameter for the Yin et al function
Maximum degree days	22.06	20.37	Degree-days accumulated at Topt
Scotophase	10	12	Hours of scotophase for diapause induction and termination

Table 3. Developmental and diapause parameters for O. nubilalis (ECB) and S. nonagrioides (MCB)

Modeling of damage to ear

Damage produced by larvae feeding activity to maize kernels was modeled according to the effects of temperature on the development of the larvae. The rate of feeding was modeled according to temperature:

$$DamageRate = EarDamageTemperature * Larvae * MaxRate \quad (12)$$

where *EarDamageRateTemperature* is the rate depending on temperature, *Larvae* is the proportional number of individuals in the larval phase, *MaxRate* is the daily maximum damage rate. The damage rate is expressed as the percentage of ear damaged by larvae. The effect of temperature on larva feeding was modeled using equation (11) adapted to larval feeding.

2.3.3. MIMYCS.Borers software component diagram

The different parts of the simulation model have been divided into single modelling strategies that have been developed as independent software component units (Figure 11). The insect borer phenology model is composed by a composite strategy in which the main software code control the flux of information from a life stage to the other, and the different single strategies simulates parts of the developmental system.

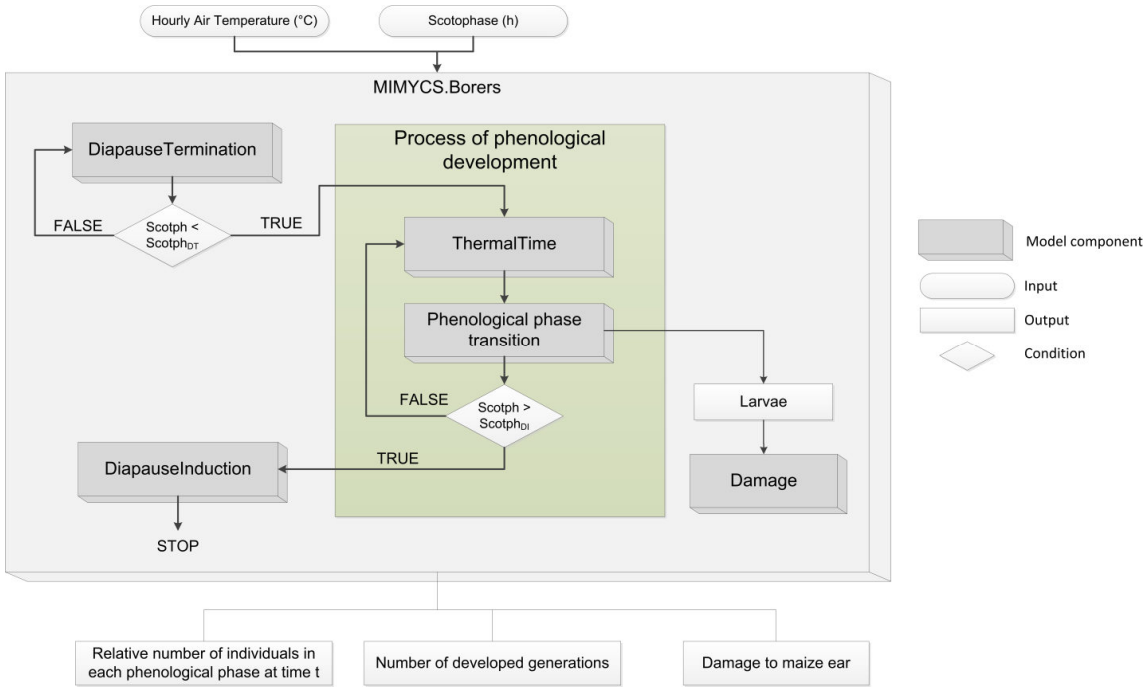


Figure 11. MIMYCS.Borers model components and sub-components. Scotph = actual scotophase; $Scotph_{DT}$ = scotophase for diapause termination; $Scotph_{DI}$ = scotophase for diapause induction

The strategy *ThermalTime* calculates the degree-days at each time step and starts after that the scotophase for diapause termination has been reached. The strategy *PhenologicalPhaseTransition* controls the number of individuals flowing from a life stage to the other. The strategy *DiapauseTermination* and *DiapauseInduction* determine the proportion of insect population terminating or entering diapause.

2.3.4. MIMYCS.Borers testing

Phenology

The MIMYCS.Borers model component was tested for its capability to simulate the phenological development of the European corn borer (ECB - *O. nubilalis*) and the Mediterranean corn borer (MCB – *S. nonagrioides*). The data source used the test the model consisted in data about date and numbers of moths caught in pheromone cone traps from surveys taken in i) the Piemonte Region in Northern Italy (ECB), and ii) different regions in Spain (MCB – data from literature). The model was test for its capability to simulate the peak (the day with the highest number of moths caught) of first generation adult flight by evaluating their accuracy, which has been evaluated using the Root Mean Square Error (RMSE, dimensionless, 0 to +∞, optimum = 0; Fox 1981), the Modelling Efficiency (EF, dimensionless, -∞ to 1, optimum =1; if negative indicates that the average of observations is a better predictor than the model; Nash and Sutcliffe 1970), and the Coefficient of Residual Mass (CRM, dimensionless, -∞ to +∞, optimum = 0, if positive indicates model underestimation, if negative indicates model overestimation; Loague and Green 1991).

Results for the ECB are shown in Figure 12, while results for the MCB are shown in Figure 13. Results of simulations showed that the model was accurate in the explored conditions, reproducing correctly the appearance of the peak of the adult flight. In both cases the data points are homogenously distributed around the 1:1 line. All the accuracy indicators are better when simulating the ECB peak. This can be due to the fact that data used for the ECB can be considered of higher quality than the ones used for the MCB. In fact, while MCB data were extrapolated from different source of literature and meteorological data were obtained from the CGMS (Crop Growth Monitoring System) of the JRC which are interpolated data on a 25x25km data grid, the ECB data were taken from an homogeneous dataset of surveys conducted in experimental trials in the

Piemonte region in Northern Italy and the meteorological data from automatic electronic stations placed close to the experimental fields. Consequently, while the results for the ECB can be already considered satisfactory (in the tested conditions), taking into account just the values assumed by the accuracy indicators, this parameterization of the model cannot yet be considered fully reliable for the use in a context of MCB pest management: the RMSE is too high, an acceptable value could be around 7, that is around one week of average error could be technically acceptable, and the model efficiency EF is too low and negative in some cases. Nevertheless, results are very promisingly and should be considered satisfactory for a number of reasons. Firstly the comparison between observed vs simulated values (Figure 2) shows that the error of the estimated points is homogenously distributed around the 1:1 line, that is without systematic patterns, meaning that the model is consistent with the MCB phenological development. Secondly, the CRM is very low, that is the model does not show a systematic tendency to under- or overestimation. Thirdly, it is true that the RMSE is somewhat high in all cases, but this is due to few points (one or two points in each tested case) with large error. In fact, the squaring process used to calculate this indicator makes it very sensitive to occasional large error. Finally, it must be taken into account that due to a lack of specific meteorological data for the years and the locations analyzed, the simulations were conducted using a 25 km x 25 km grid interpolated temperature data (i.e., the JRC-CGMS dataset), and this could have significantly influenced the accuracy of simulations. overall the results showed that the model is consistent with the phenological development of the MCB, but it needs to be further evaluated with more data preferably coming from weather station located close to the MCB monitoring traps, instead of using interpolated data, which were the only ones available for this work. Furthermore, in order to have a more careful idea of the accuracy of the model, more data would be needed and possibly from surveys specifically collected to test the model, and not from the available literature, in order to avoid problems related to different protocols and methods used to collect them.

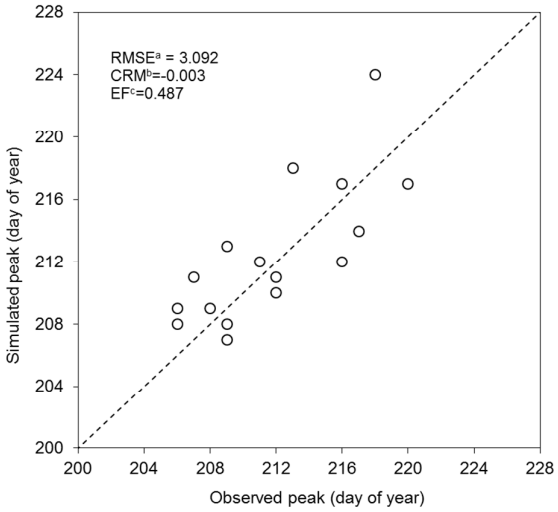


Figure 12. Observed vs predicted day (days from January, 1) of occurrence of the first generation adult flight peak of the European Corn Borer in Northern Italy

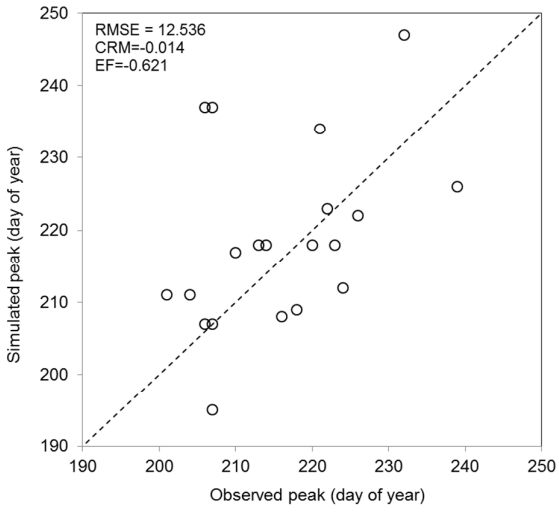


Figure 13. Observed vs predicted day (days from January, 1) of occurrence of the first generation adult flight peak of the Mediterranean Corn Borer in different regions in Spain.

Larval damage

The MIMYCS.Borer component was calibrated for simulating the damage provoked by larvae to maize ears and the optimized model was evaluated according to RMSE, CRM, and EF indicators. Parameters MaxRate and the optimum temperature for larval feeding were calibrated using data of larval damage observed in different experimental field in Northern Italy.

The model was calibrated using a least square optimization method. Following results of optimization, optimum temperature for feeding was 35°C and feeding rate 1.1 ear(%) d^{-1}. Figure 14 shows the plot of the optimized observed vs simulated ear damage. According to the indicators and to the plot, the model was acceptable in the simulation of larval damage. The RMSE is low, the EF is

positive meaning that the model is better predictor than the average of the observed values, and the CRM shows a tendency to underestimation.

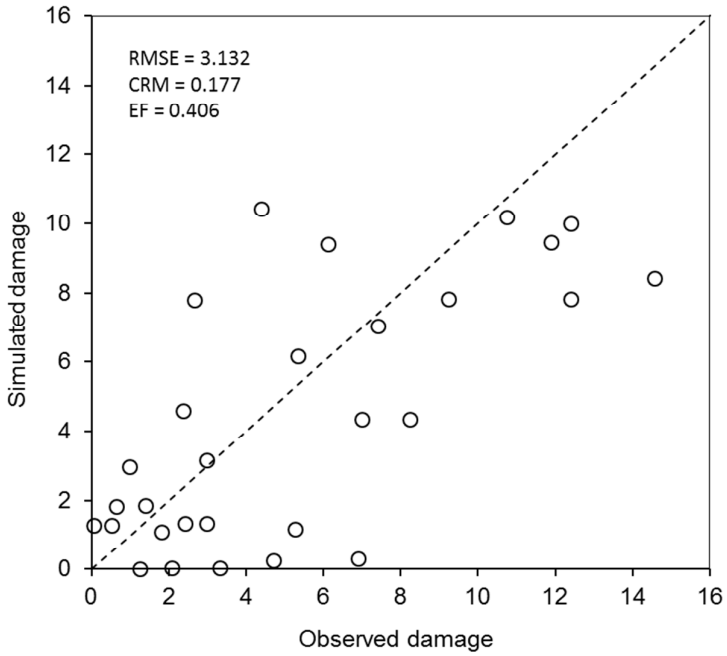


Figure 14. Observed vs simulated damage to ear (%). Data from Northern Italy. Dottel line is the 1:1 line. Accuracy indicators are showed.

2.4. The MIMYCS.Fungi model component

2.4.1. MIMYCS.Fungi conceptual model

Information on the three fungi considered in this work were generalized and organized in a relational diagram showing the processes leading to fungi infection and mycotoxin contamination in maize kernels (Figure 15).

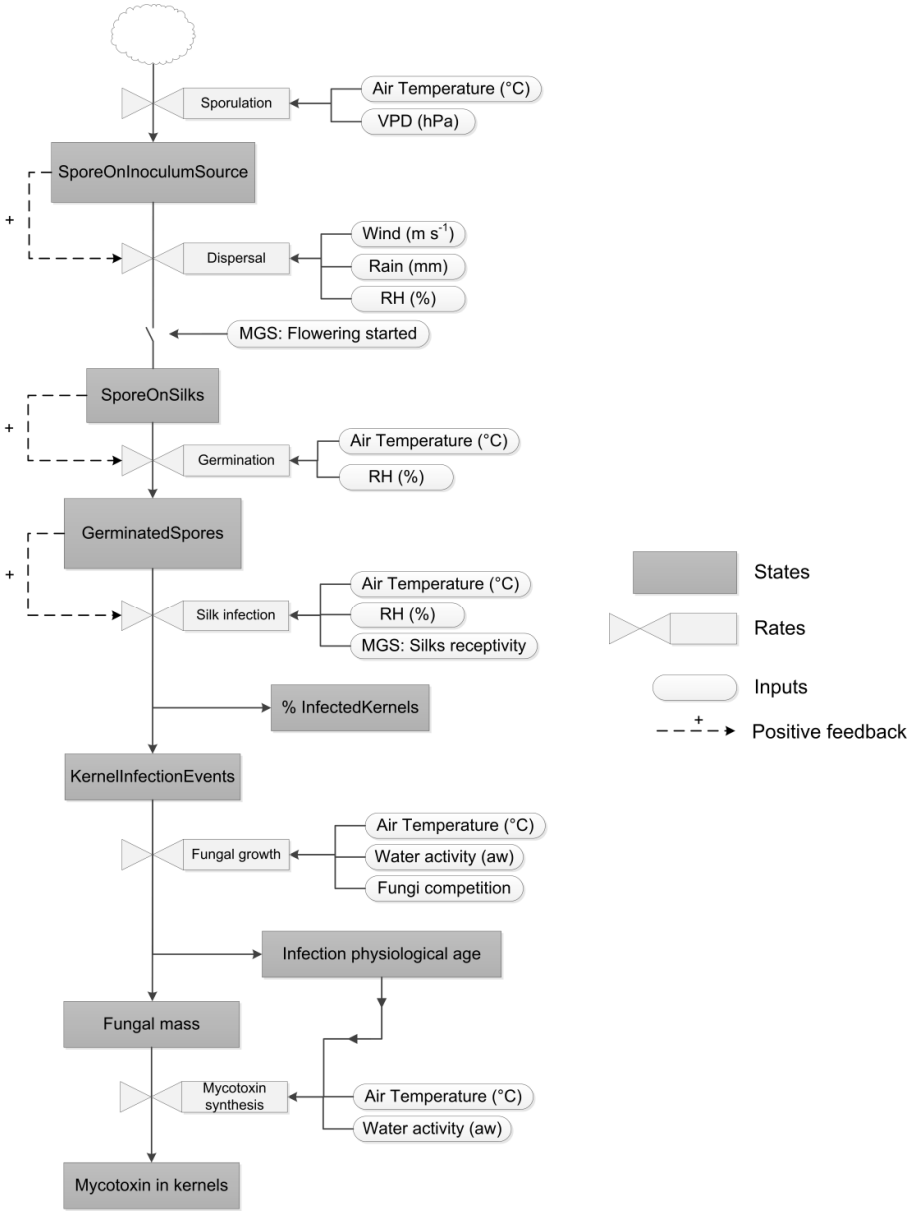


Figure 15. MIMYCS.Fungi conceptual model. MGS=Maize growth stage

The diagram was considered appropriate for *F. verticillioides*, *F. graminearum*, and *A. flavus* as their pattern of development is very similar. Differences will be discussed in the following paragraph.

Spore on inoculum source are produced through a rate of sporulation. Spores are then dispersed through a rate of dispersal which is proportional to the spores on the inoculum source. Once that maize reaches the flowering stage, dispersed spores can land on silks. Spores on silks germinate through a germination rate giving origin to kernel infection by fungi. Depending on when

the infection start each kernel infection event is characterized by a specific infection physiological age determined by the same fungal growth rate. The fungal mass developing in kernels synthesize mycotoxins according to a mycotoxin synthesis rate.

2.4.2. MIMYCS.Fungi model development

Most of the equations used for the development of the model were taken from http://agsys.cra-cin.it/tools/.

Sporulation

Sporulation rate was modeled according to air temperature (T°C) and vapor pressure deficit (VPD). Sporulation rate is calculated as the product of a relative rate depending on T°C and a relative rate depending on VPD:

$$SporulationRate = SporulationRateTemperature \times SporulationTemperatureVPD \quad (13)$$

The relationship between temperature and sporulation was described through a beta function by Yin et al (1995). The function is expressed here in its generic form as it has been used for MIMYCS.Fungi for all the processes responding to temperature with a non-simmetrical sigmoid shape. The equation:

$$r(T) = \left(\left(\frac{T(h) - T_{min}}{T_{opt} - T_{min}} \right) \left(\frac{T_{max} - T(h)}{T_{max} - T_{opt}} \right)^{\left(\frac{T_{max} - T_{opt}}{T_{opt} - T_{min}} \right)} \right)^{c} \quad (14)$$

where *r(T)* is the rate (in this case the *SporulationRate*), *T(h)* is hourly air temperature, *Tmin*, Topt, and Tmax are respectively the minimum, the optimum, and the maximum temperature for the modeled process, in this case the sporulation. The parameter *c* is the only fitting parameter which can be parameterized when enough reference data are available. On the contrary, the generic default value *c* = 2 was used.

The relationship with VPD was described through a logistic function:

$$r(VPD) = \frac{1}{1 + e^{(-a + b * VPD)}} \quad (15)$$

where

$$a = -4.59512 * \frac{\frac{VPDmin}{VPDmax} + 1}{\frac{VPDmin}{VPDmax} - 1}$$

$$b = \frac{1}{VPDmax} * (a + 4.59512)$$

where *VPD* is the actual vapor pressure deficit, *VPDmin* is the value of *VPD* at which *r(VPD)* is at its optimum, *VPDmax* is the maximum value of *VPD* at which sporulation takes place.

Dispersal

Dispersal was modeled according to the effects of rain and wind (Waggoner and Horsfall 1969; Waggoner 1973; Aylor 1978). Their combined effect was assumed as additive:

$$DispersalRate = WindDispersalRate + RainDispersalRate \quad (16)$$

The relationship with Wind was described through the following equation:

if wind ≤ Wind50

$$WindDispersalRate = \frac{(Wind - WindMin)^2}{(Wind - WindMin)^2 + (Wind50 - WindMin)^2} * WindMaxRate \quad (17)$$

if wind > Wind50

$$WindDispersalRate = \frac{(Wind - WindMin)^2}{(Wind - WindMin)^2 + [(Wind50 - WindMin)^2 * c]} * WindMaxRate \quad (18)$$

Where

$$c = -\frac{1}{(WindMax - Wind50} + \left[1 + \left(\frac{1}{WindMax - Wind50}\right) * Wind50\right] * Wind \quad (19)$$

where: *Wind* = wind daily mean speed (m s^{-1}), *WindMaxRate* = maximum proportion of spores that can be detached by wind, *WindMin* = minimum wind speed for spore detachment (m s^{-1}), *WindMax* = wind speed for the detachment of *WindMaxRate*, *Wind50* = wind speed for the detachment of 50% of spores.

The relationship with rain was described according to Waggoner and Horsfall (1969) through the following equation:

$$RainDispersalRate = RainMaxDispersal * \frac{\frac{Rain}{LAI}}{Rain50 + \frac{Rain}{LAI}} \quad (20)$$

where: *Rain* = daily precipitation (mm), *LAI* = Leaf Area Index (m^2 m^{-2}), *RainMaxDispersal* = maximum proportion of spores that can be detached by wind, *Rain50* = precipitation for the detachment of 50% of spores.

Differently from *F. verticillioides* and *F. graminearum*, according to Battilani et al. (2012) the dispersal of *A. flavus* is not possible during rainy days and when relative humidity >75%. Consequently, the dispersal of *A. flavus* was modeled accordingly.

After the appearance of silks (flowering) dispersed spores land on silks and can germinate.

Germination

Germination was modeled according to air temperature (%), and air relative humidity (%), according to:

$$GerminationRate = MaxGerminationRate * GerminationT * GerminationRH \quad (21)$$

where *MaxGerminationRate* is the maximum proportion of spores that can germinate in one hour in optimum conditions of temperature and relative humidity, *GerminationT* is the germination rate according to temperature, and GerminationRH is the germination rate accordeing to relative humidity. The relationship with air temperature was described using equation (14) parameterized for germination. The relationship with air relative humidity was modeled through the equation:

$$GerminationRH = e^{b(100-RH)} - c * e^{b*(100-RHmin)} \quad (22)$$

where

$$c = \frac{100}{100 - RHmin} - \frac{RH}{100 - RHmin}$$

where *RH* is the air relative humidity (%), *RHmin* is the minimum relative humidity for spore germination, and *b* is a shape parameter.

Each proportion of spores germinating at each time step *h* is modeled as an independent cohort of fungal infection event which then infect kernels and synthesizie mycotoxins independently from the other cohorts.

The state GerminatedSpores (Figure 15) is the result of the sum of the infection events of all the cohorts of germinated spores.

Silk Infection

For each cohort of germination events a silk infection rate is calculated which determines the progressive percentage of infected kernels infected by that cohort of germination events and gives origin to new cohorts of kernel infection events representing fungal mass colonizing kernels. A schematic representation of the 'cohort approach' is shown in Figure 17.

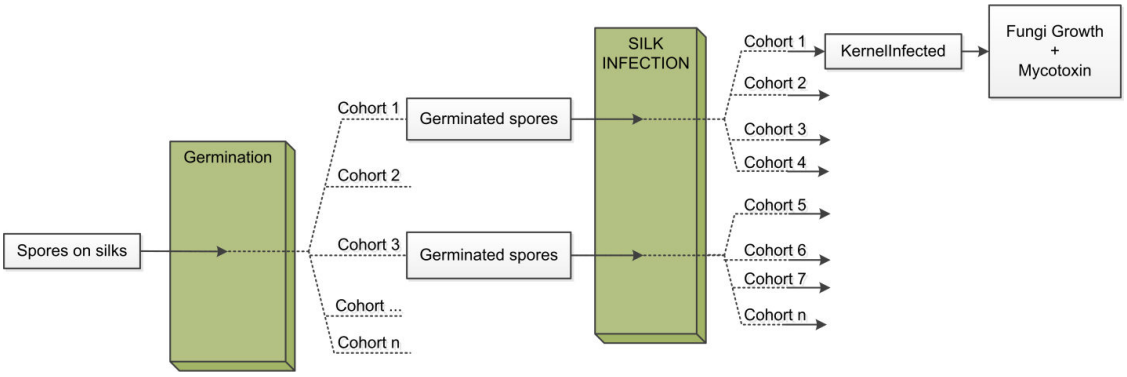


Figure 16. Schematic representation of the cohort approach for the development of kernel infection

Silk infection is modeled through a silk infection rate varying according to air temperature, relative humidity (%), and silks receptivity, according to:

$$SilkInfectionRate = SilkInfTemperature * SilkInfRH * SilkReceptivity \quad (23)$$

where *SilkInfTemperature* is the silk infection rate according to temperature, *SilkInfRH* is the silk infection rate according to air relative humidity (%), and *SilkReceptivity* is the silk infection rate according to silk receptivity. The relationship with air temperature was described using equation (14) parameterized for silk infection (for this first version of MIMYCS.Fungi the same parameterization used for germination was used). The relationship with relative humidity was

described using equation (22) and the same parameterization used for germination. Silk receptivity was modeled according to Headrick et al. (1990), Reid et al. (1992), Reid et al. (2002), Stewart et al (2002), and Marsh and Payne (1984), and using a fuzzy-logic approach (Zadeh 1965). According to the mentioned authors, for *F. verticillioides* and *A. Flavus*, colonization of maize silks is optimum at the onset of silk senescence. Differently, *for F. graminearum* the greatest disease severities are observed when silks are infected during the early stages of development, with a peak in susceptibility around 1-6 days after silk emergence, followed by a rapid decrease in susceptibility when silks starts to senesce. According to these information, it was assumed that (i) for all the fungi, silk infection starts at silk emergence, (ii) for F. graminearum the optimum peak is at the starting of grain filling, when silks are still green, and then susceptibility of silks decreases rapidly to zero at milk maturation, when silks start to senesce (Nielsen 2011), (iii) for *F. verticillioides* and *A. flavus* have the optimum peak is at milk maturation and susceptibility decrease to zero at dough maturation when silks are completely dry (Nielsen 2011). The relationship of the three fungi with silk development is schematically represented in Figure ZZZ. The different silk developmental phases are determined according to accumulated degree-days calculated by the model CropSyst integrated in MIMYCS.

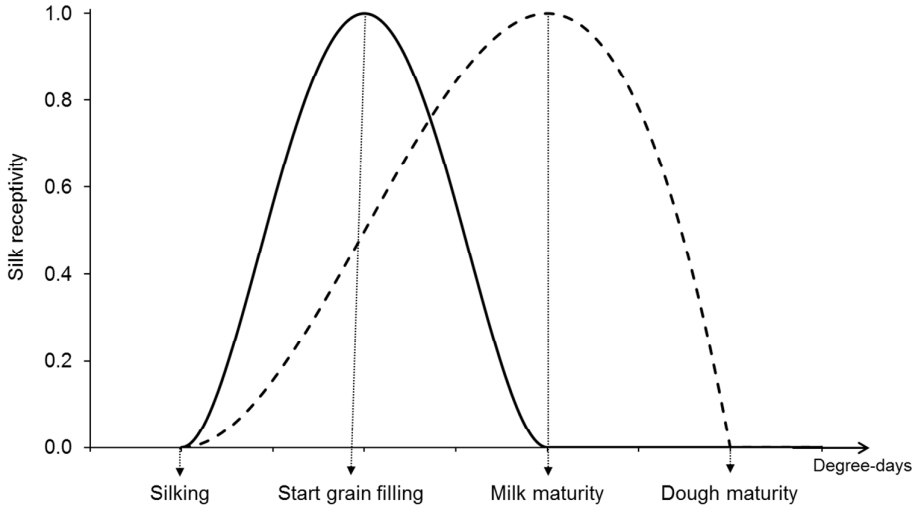


Figure 17. Schematic representation of silk receptivity to fungal infection by *F. graminearum* (solid line) and *F. verticillioides* and *A. Flavus* (dotted line)

Fungal growth

Fungal growth is modeled through a fungal growth rate varying according to air temperature, kernel water activity, and fungal competition inside kernels according to:

$$FungalGrowth = FungalGrowthTemp * FungalGrowthAw * FungalCompetition \qquad (24)$$

The relationship with air temperature was described using equation (14) parameterized for fungal growth. The relationship with water activity was parameterized using equation (22) adapted to water activity and parameterized for fungal growth.

Fungal competition was modeled according to information from literature (see paragraph 1.2.1 page 6). Fungal competition was modeled, using a fuzzy logic approach, as a coefficient varying from 0 (fungus not competitive) to 1 (fungus highly competitive) applied to fungal growth and taking into account the two most important variables influencing fungal growth and competition in maize kernels: temperature and water activity. Other factors were not taken into account. Optimum level of competition (competition = 1) were fixed arbitrarily according to literature, while minimum levels (competition = 0) were set equals to parameters used for fungal growth. Figure 18 and Figure 19 show how the coefficient varies according to water activity and temperature. The competition coefficient was modeled using a broken linear approach for both temperature and

water activity. As a consequence, for both temperature and water activity the parameters required are: minimum value, start of optimum value, end of optimum value, maximum value.

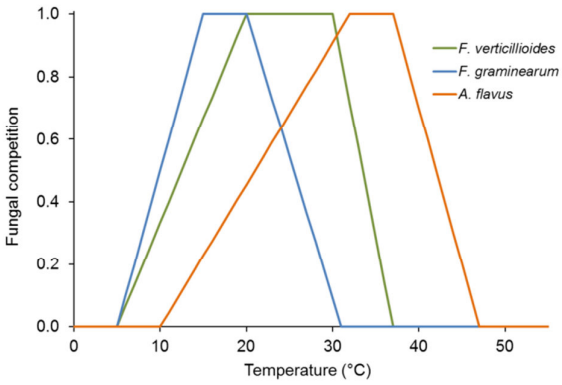


Figure 18. Fungal competition coefficient according to air temperature

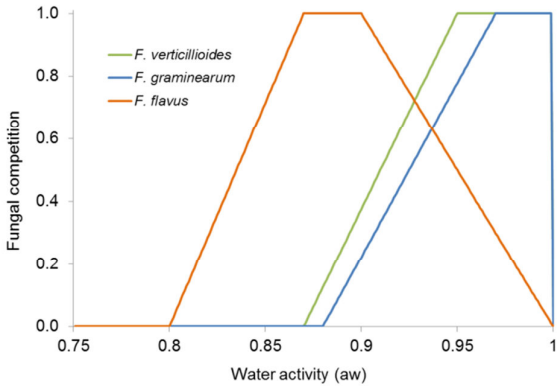


Figure 19. Fungal competition coefficient according to water activity

Mycotoxin synthesis

Mycotoxin synthesis is modeled according to a mycotoxin synthesis rate according to air temperature, water activity, and a mycotoxin synthesis time-dependent rate (0 to 1) depending on the physiological age of the fungal infection cohort according to:

$$MycotoxinSynthesis = MycotoxinTemp * MycotoxinAw * MycotoxinTimeDependent \quad (25)$$

The relationship with air temperature was described using equation (13) parameterized for mycotoxin synthesis. The relationship with water activity was parameterized using equation (21) adapted to water activity and parameterized for mycotoxin synthesis.

The *MycotoxinTimeDependent* relative rate is based on the time required for a fungus cohort to reach the maximum mycotoxin synthesis rate since the starting of infection. The time since the starting of the infection was modeled as a physiological age for each cohort of kernel infection events. The computation of the physiological age for a single fungus cohort was based on the rate summation method detailed by Curry and Feldman (1987) which is based on the concept that development rates are additive for changing temperatures. In this way, multiplying the reciprocal of the days required to reach the maximum toxin synthesis rate to the sum of FungalGrowth rates, the physiological age for a specific kernel infection events can be calculated. As an equation:

$$KernelInfectionEventPhysAge(t) = \frac{1}{DaysToToxMaxRate} \sum_{i=0}^{t} FungalGrowth \quad (26)$$

where *KernelInfectionEventPhysAge(t)* is the physiological age of the actual kernel infection event at time *t*, *DaysToToxMaxRate* is the time required (days) to reach the toxin synthesis maximum rate, *FungalGrowth* is the fungal growth rate of Equation (24).

The toxin synthesis rate varies following a sigmoidal shape until the reaching of the maximum rate. The relationship between the kernel infection physiological age and the toxin synthesis rate was modelled using the logistic equation (15) adapted to toxin synthesis rate calculation.

Parameterization

The model MIMYCS.Fungi was parameterized according to data and information found in literature. Table 4 shows the list of the parameters of MIMYCS.Fungi, their parameterization for each fungus, and the reference used to parameterize it. Most of the shape parameters required by

the different function are not shown in Table 4 as for each of them a default value was used for all the fungi: in fact not enough data for specific parameterization for each of the three fungi were found available in literature. The shape parameters and the default value used are:

- process of germination, shape parameter *b* of equation (22): *b*=-0.1
- process of fungal growth, shape parameter *b* of equation (22) adapted to water activity effect: *b*=-20
- all the processes using equation (14) for describing the effect of temperature, shape parameter *c*=2;

	Fusarium verticillioides		*Fusarium graminearum*		*Aspergillus flavus*	
	Value	Reference	*Value*	Reference	*Value*	Reference
Sporulation						
Tmin	5	(Battilani et al. 2004; Rossi et al. 2009)	5	(Sutton 1982; Rossi et al. 2003; Schmale III 2003)	5	(Rai et al. 1967; Sauer and Tuite 1987; Giorni et al. 2012)
Topt	27		30		30	
Tmax	45		35		45	
VPDmax	4		4		7	
VPDmin	0.5*		0.5*		3	
Dispersal						
MaxSporeDipsersalRateRain	0.8*	(Jones and Harrison 2004; Paul et al. 2004; Maiorano et al. 2009)	0.8*	(Rossi et al. 2002; Jones and Harrison 2004)	0.8*	(Battilani et al. 2012)
MaxSporeDipsersalRateWind	0.8*		0.8*		0.8*	
RainDispersal50	1		1		0	
WindMaxDispersal	6*		6*		6*	
WindMinDispersal	3*		3		3*	
Wind50Dispersal	5*		5*		5*	
Germination and silk infection						
PropSporesGermOptConditions	0.16	(Armolick and Dickson 1956; Marin et al. 1996; Torres et al. 2003)	0.1	(Marin et al. 1996; Beyer et al. 2004)	0.18	(Marín et al. 1998)
MinRH (%)	87.5		85		84	
Tmin	5		5		15	
Topt	25		25		37	
Tmax	37		31		47	
Fungal growth in kernels						
Tmin (°C)	5	(Marin et al. 1996; Etcheverry et al. 2002; Samapundo et al. 2005)	5	(Stewart et al. 2002; Hope et al. 2005; Ramirez et al. 2006)	10	(Samapundo et al. 2007; Giorni et al. 2011)
Topt (°C)	25		25		35	
Tmax (°C)	40		35		47	
awMin (aw)	0.88		0.90		0.80	
awShapeParameter	-20					
Toxin synthesis in kernels						
Tmin (°C)	10	(Marin et al. 1999a, 1999b; Battilani et al. 2003)	12	(Hope et al. 2005; Ramirez et al. 2006)	10	(Schindler et al. 1967; Giorni et al. 2011)
Topt (°C)	28		28		25	
Tmax (°C)	37		37		35	
awMin (aw)	0.93		0.94		0.88	
Fungal Competition						
Tmin	5	(Marin et al. 1996; Etcheverry et al. 2002; Samapundo et al. 2005)	5	(Stewart et al. 2002; Hope et al. 2005; Ramirez et al. 2006)	10	(Samapundo et al. 2007; Giorni et al. 2011)
ToptStart	20		15		32	
ToptEnd	30		20		37	
Tmax	40		31		47	
awMin	0.87		0.88		0.80	
awOptStart	0.95		0.97		0.87	
awOptEnd	1		1		0.90	
awMax	1		1		1	

Table 4. MIMYCS.Fungi parameters, values for each fungus and references

2.4.3. MIMYCS.Fungi software component diagram

The different parts of the simulation model have been divided into single modelling strategies that have been developed as independent software component units (Figure 20).

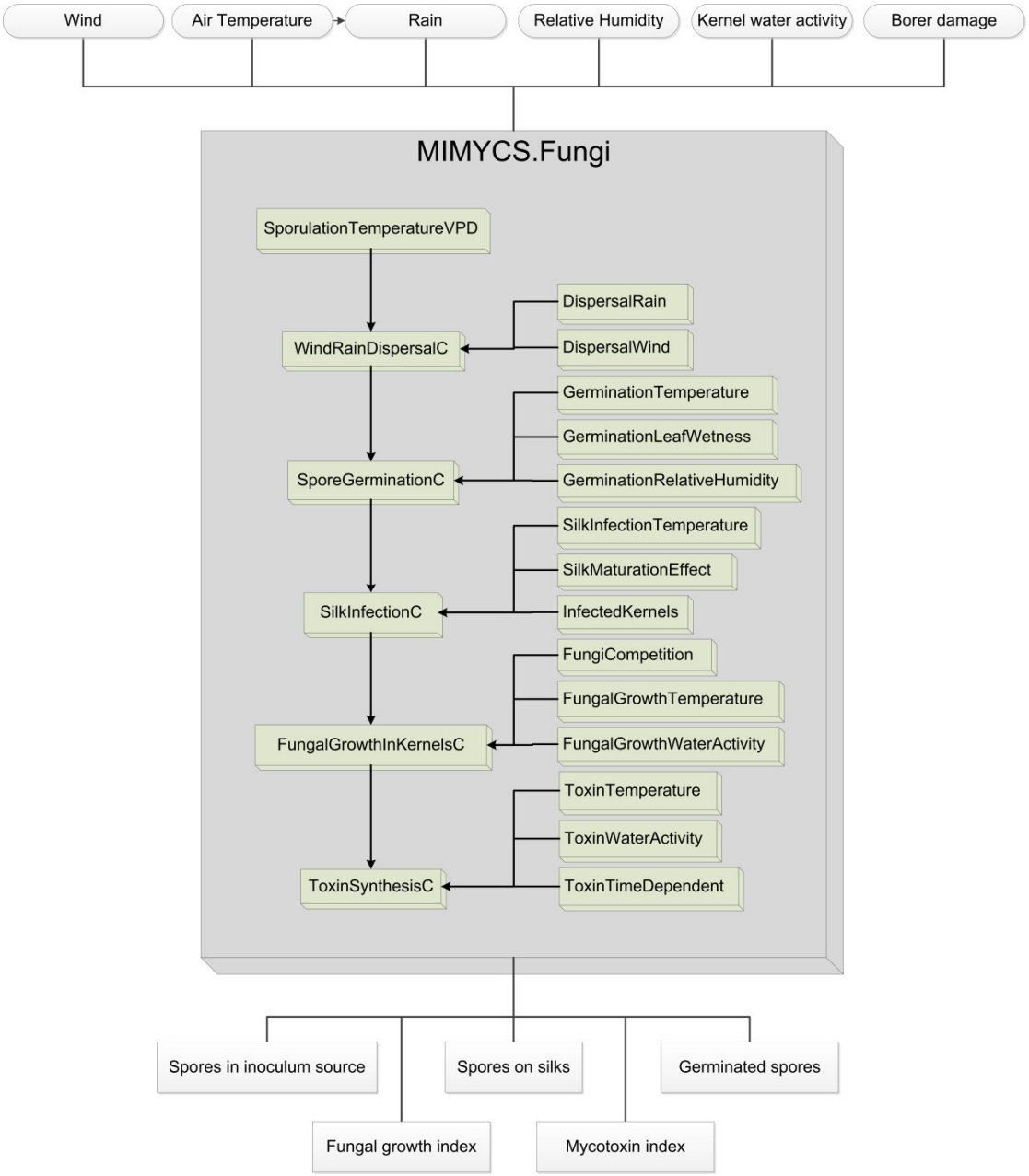


Figure 20. MIMYCS.Fungi model components and sub-components.

2.4.4. MIMYCS.Fungi testing

The model MIMYCS.Fungi was plan to be tested with data coming from extension services in Spain, France, and Italy, as described in the project proposal. Contacts were established to verify the existence and availability of such data. However, the provided data resulted not adequate for testing the relevant MIMYCS model. In fact, provided data came from samples collected in farm maize field, with no replications, in most cases without following an adequate sampling

methodology, and with samples analysed using different lab methodologies. The sampling problem become evident evaluating data: samples coming from the same location and from the same or very similar agro-climatic conditions showed a very high variability in mycotoxin contamination.

Consequently MIMYCS was not tested against observed mycotoxin contamination. Nevertheless, due to the interest of the private company Syngenta and to the collaboration agreement with them (see Section 5, paragraph 5.1.4), data about mycotoxin contamination since 2004 coming from different experimental fields in Northern Italy will be made soon available for testing and calibrating MIMYCS.

2.5. MIMYCS software component diagram

All the developed model components were integrated together in the framework MIMYCS. Figure XX shows the software component diagram of the framework MIMYCS.

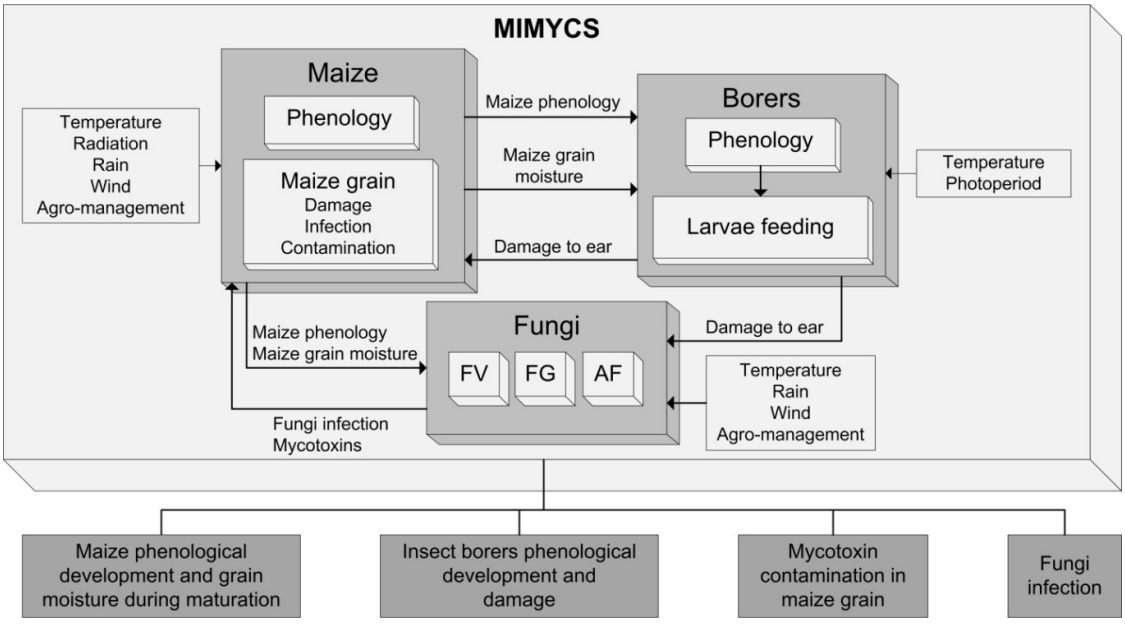


Figure 21. MIMYCS software component diagram

Section 3. APPLICATION OF MIMYCS AND OF MIMYCS COMPONENTS. FURTHER DEVELOPMENTS

Abstract

MIMYCS models were applied to conduct simulated experiments to address questions concerning system components behavior under alternative agro-climatic scenarios under different European maize areas. An insect winter survival model, which was not initially included in the project planning, was also developed and added to MIMYCS.Borers in order to conduct studies about potential distribution of insect pest. First applications of MIMYCS have included: (i) development of a winter survival model and analysis of the potential distribution of the Mediterranean corn borer in Europe (work published in an international congress peer-reviewed paper), (ii) comparison between two different methods for predicting the peak of adult flight in Northern Italy for pest management purposes (work published in the ISI journal International Journal of Biometeorology), (iii) comparison between different methods for simulating the phenological development of insect and mapping their potential distribution (work published in the ISI journal Ecological modelling), (iv) mapping of the potential distribution and risk of contamination of three main mycotoxins in maize kernels in Europe under different climate conditions.

3.1. Development of an insect winter survival model

MIMYCS.Borers was further developed including the development of a larval winter survival model which was not initially included in the project MIMYCS. The model was developed in order to allow the conduction of studies about the probabilities of survival of an insect in specific areas, in order to evaluate limiting factors for survival and the possible change of area of development under climate change variability. The model was applied to the case of the MCB in Europe. This work was published in an international congress peer-reviewed paper presented at the International Environmental Modelling and Software Society Congress, in Leipzig, July 2012.

3.1.1. Introduction

Insects are poikilotherms (i.e., body temperature varies along with that of the environmental temperature), hence their development, geographical distribution and population density are strongly influenced by temperature. As a consequence, a warming climate has the potential to significantly modify the actual distribution and development of insects, including agricultural insect pests, with unknown consequences in agricultural systems (Gutierrez et al. 2010). In this work we analyzed the case of the Mediterranean Corn Borer (MCB) Sesamia nonagrioides Lefebvre, which is one of the most important maize borers in Europe. This pest develops through four main stages: egg, larvae, pupae, and adult, and it overwinters as a diapausing larva in maize stalks and roots. Gillyboeuf et al. (1994) reported that its distribution and population levels are primarily determined by its sensitivity to sub-zero winter temperatures. In Europe its spread and development have been mainly reported from the coastal regions of the Mediterranean basin, (up to four generations per year), and of the Atlantic coasts up to the French coasts of the western Loire region (one or two generations) (Eizaguirre and Fantinou 2011). No study has estimated the potential spread of the MCB considering the overwinter survival including the fraction of larvae in the maize roots, liking survival to a phenological model. This paper presents the preliminary results of a study conducted to analyze the role of temperature in the potential distribution of the MCB in Europe under current conditions and warming climate.

3.1.2. Winter survival model

The data source used for the development of the survival model consisted of data about mortality (%) in diapausing cold-acclimated larvae of MCB following exposure to cold temperatures (-10.8°C, -4°C, -2°C, 0°C) and different time exposure (from 2 to 64 hours) obtained by Gillyboeuf et al. [1994] and Andreadis et al. [2011]. Since these data showed that a relationship between temperature, time exposure, and mortality was evident at temperatures ≤-2°C, this temperature was fixed as a threshold for calculating mortality, while the average of mortality at 0°C was used in the model as intrinsic diapausing larvae mortality (Mint, %). Probit analysis [Finney 1971] was performed for estimating the lethal time (hours) for 90% of mortality (LT90) at the tested sub-zero temperatures. Following results of probit analysis, a thermal death time curve (TDTC) representing LT90 at any temperature ≤-2°C was determined. Mortality (%) at any temperature ≤-2°C and time exposure (h) was then calculated as a proportion of 90% mortality (from TDTC curve). The proportion was calculated through the relationship existing between the proportion of LT90 (pLT90 – equal to the actual time exposure divided by LT90), and the proportion of actual mortality (pM90 – equal to the actual mortality divided by 90%). The proportion of 90% mortality was calculated using the logarithmic function:

$$pM_{90} = a * \ln(b * pLT_{90} + 1) \quad (27)$$

where a and b are fitting parameters obtained by optimizing eq. (1) to the observed pM90 data from Gillyboeuf et al. (1994) and Andreadis et al. (2011) (least-squares method, Microsoft Excel Solver). The function is limited by a plateau fixed at Mmax/90 which is the proportion of maximum mortality (Mmax=100), that is equal to 1.11. Finally, actual mortality (Mi, %) is calculated as the

product of 90% per pM90. Thus, at each time step i during diapause, if hourly temperature is ≤-2°C, the rate mortality Mi is calculated and the following rule is applied:

$$if \quad M_i > (S_0 - S_{i-1}), \qquad then \quad S_i = S_0 - M_i\,, \qquad else \quad S_i = S_{i-1} \tag{28}$$

where S0 is the relative starting level of population (given by 100-Mint, %), Si are actual survivors, and Si-1 are survivors at time i-1. In this way, it is assumed that sub-zero temperatures operate a negative selection on the population: the proportion of individuals that survive to a specific time exposure and temperature are killed by higher time exposure and/or lower temperatures. The effect of temperature is additive only if negative conditions appear on consecutive hours. Gillyboeuf et al. (1994) estimated that around 70%-85% of MCB larvae overwinter in maize residues above the soil surface, and the remaining larvae in roots (up to 10 cm below the soil surface). Consequently, two modelling solutions were implemented and compared for the simulation of winter survival: the first one (AirMS) using as input only air temperature, the second one (AirSoilMS) using air and soil temperature. Soil temperature in the first 10 cm was estimated using the model component UNIMI.SoilT coupled to the UNIMI.SoilW component (http://agsys.cra-cin.it/tools/) for simulating water balance, being soil water content a needed input to estimate soil temperature. Only one synthetic soil profile, representing a loam soil in flat land, was simulated. It was assumed that 20% of diapausing population was overwintering in roots, and 80% in maize stems above soils surface in the modelling solution taking into account soil temperature. The development model was started if at the end of diapause survivors were ≥10%.

3.1.3. Phenological model

The phenological model used for the work was the generic model MIMYCS.Borers described in Section 2, paragraph 2.3 (page 23), using the parameterization for the Mediterranean corn borer.

3.1.4. Climate scenarios

A dataset of weather data on scenarios of future climate, suitable for use with biophysical models, has recently become available from the European Commission, derived from the ENSEMBLE scenarios (Donatelli et al. 2012a), and covering Europe with a grid of 25 x 25 km. Three climate scenarios were chosen as inputs for the simulation experiment: the baseline, representing a sample of 10 years of daily weather centered on the year 2000, and the IPCC emission scenario A1B centered on 2030 and 2050. The aim was to estimate potential distribution and development in the future temperature regime compared to current conditions. The realization of the A1B scenario originated from runs of the ECHAM5-R3 global circulation model coupled to the HIRHAM5 RCM for the downscaling.

3.1.5. Results and discussion

Figure 22 and Figure 23 show the thermal death time curve for 90% mortality and the curve of proportion of 90% mortality used in the survival model. The thermal death time curve is characterized by a point of strong discontinuity at -4°C: this temperature has been reported to be starting point of freezing of extra-cellular ice nucleating agents (INA) present in insect species classified as freeze-tolerant, like the MCB (Bale and Hayward 2010; Andreadis et al. 2011): the presence of INA gives the insect the ability to adapt to sub-zero temperatures, but the formation of ice can cause damaging deformation to cells (Mazur 1984).

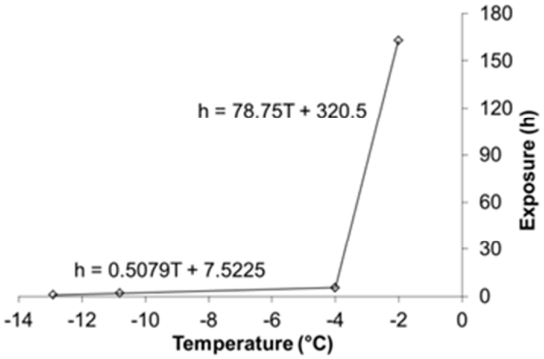


Figure 22. Thermal death time curve indicating the required exposure to cause 90% of mortality

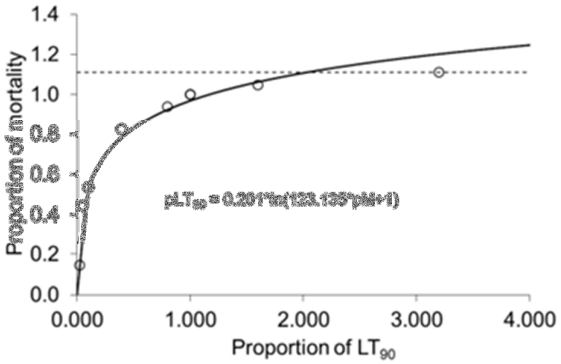


Figure 23. Proportion of 90% mortality as a function of the proportion of lethal time for 90% mortality (LT90). Dotted line represents the maximum proportion of mortality

3.1.6. Mediterranean corn borer survival

Results of MCB simulated survival potential across Europe are showed in Figure 24a and Figure 24b (AirMS results), and Figure 24c and Figure 24d (SoilAirMS results). Results are shown in terms of difference between the areas of potential distribution of baseline (gray areas) and 2030 and 2050 scenarios (green areas). The most evident difference between the two approaches is the area interested by potential survival under the baseline: the AirMS estimates a potential distribution which is much more limited compared to the SoilAirMS.

The potential distribution estimated by AirMS include mainly the Mediterranean and Atlantic coastal regions of Europe which are already known from literature to be areas with high population levels of MCB with important impacts on cultivated maize. Thus, these results confirm that in these areas temperature does not represent a limiting factor for MCB survival and spread. Results coming from SoilAirMS approach are more interesting because represent a closer to reality estimate under current conditions. Interestingly, SoilAirMS survival simulations show that the estimated potential distribution is extended to almost all the areas of Europe where maize is cultivated, including areas of Northern Europe where the presence of the MCB has never been reported (Eizaguirre and Fantinou 2011). As a consequence, since it is known that the populations of MCB larvae overwintering in roots can give origin, alone, to important levels of populations during the maize growing season (Gillyboeuf et al. 1994), these results indicate that overwinter temperature could not be the limiting factor determining the potential distribution of this species across Europe, and that other factors might be more important than expected. These factors might include the percentage of the larval population that escaping the critical photoperiod in autumn exposes eggs to later winter temperatures (Eizaguirre and Fantinou 2011), sowing date that influence maize phenology and the percentage of diapausing larvae (Eizaguirre et al. 2007), MCB parasitoids (Alexandri and Tsitsipis 1990), and viruses of the Baculoviruses group reported to be endemic in northern population of MCB (Gillyboeuf et al. 1994). It must also be noticed that in this work each run of simulation is independent from the others, that is, the ten years were treated independently and not as a time series, meaning that possible cumulative negative effects of consecutive hard winter conditions were not considered. For what concerns the estimated increase in potential geographical distribution, Figure 24 shows that in both cases (AirMS and SoilAirMS) the potential distribution of MCB is expected to increase under 2030 and 2050, but the main increase is expected under 2030 scenario, while under 2050 scenario the increase is less marked.

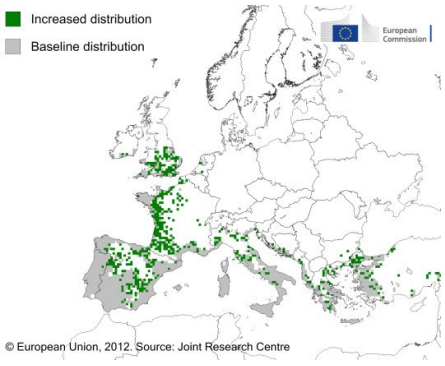


Figure 24a – AirMS, 2030 vs baseline

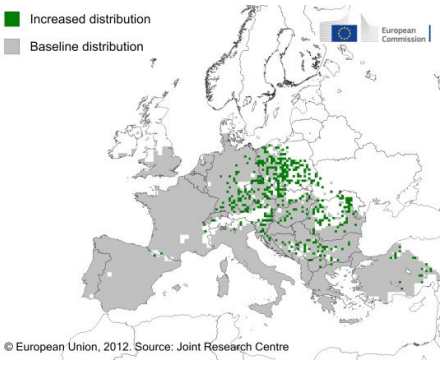


Figure 24c – SoilAirMS, 2030 vs.Baseline

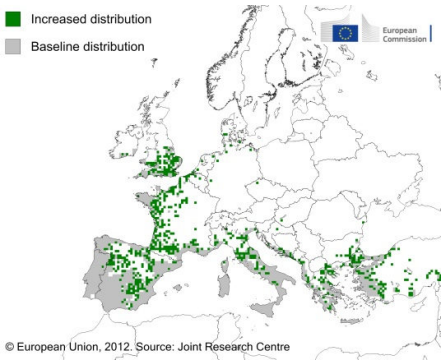


Figure 24b – AirMS, 2050 *vs* Baseline

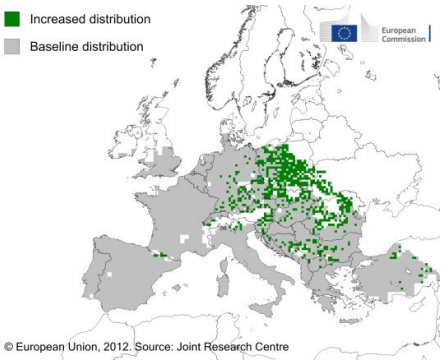


Figure 24d – SoilAirMS, 2050 *vs* Baseline

Figure 24. Difference in the estimated potential distribution between baseline (grey) and 2030-2050 scenarios (green) estimated by AirMS (air temperature as input, 23a-23b), and SoilAirMS (soil and air temperature as input, 23c-23d).

3.1.7. Mediterranean corn borer potential phenological development

Results of potential phenological development of MCB in Europe are shown in Figure 5. Results are shown in terms of absolute differences between the average potential number of generations estimated for the baseline and the 2030 and 2050 scenarios, using the two modelling solutions. The projections suggest an overall very slight increase (+0.2 - +0.6 generations) of more suitable conditions for the MCB in almost all the areas where it developed under the baseline. Most of the increase >0.6 generations is detectable in the areas where an increase in potential distribution is expected, due to the absence of development during baseline. This effect of warming climate might indicate that the increased temperatures in the areas where MCB is known to be already an important pest of maize might represent a stressful condition for the insect leading to a not substantial modification of its development.

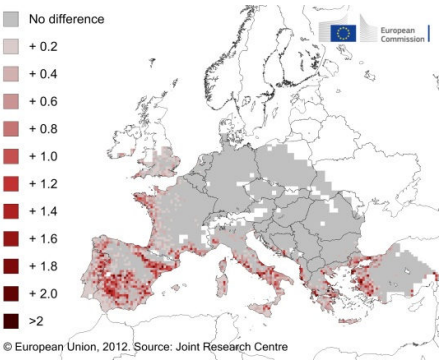


Figure 25a – AirMS, Baseline *vs* 2030

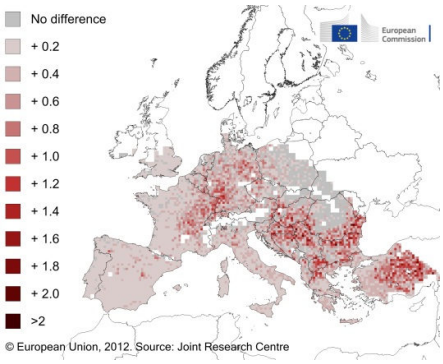


Figure 25c – SoilAirMS, Baseline *vs* 2030

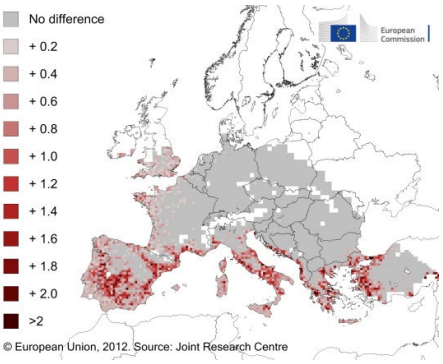


Figure 25b – AirMS, Baseline *vs* 2050

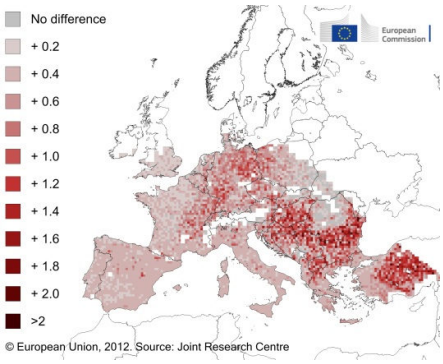


Figure 25d – SoilAirMS, Baseline *vs* 2050

Figure 25. Differences in the potential number of generation between baseline and 2030-2050 scenarios according to AirMS (24a-24b) and SoilAirMS (24c-24d)

3.1.8. Conclusions

The general trend of MCB response to future weather scenarios estimates a modest potential increase in the geographical distribution and the number of generations per year. The results of the simulations under the baseline scenario showed a potential distribution in areas where the MCB has never been reported, indicating that overwinter temperature might not be the limiting factors in determining MCB geographical distribution, and consequently that the effect of warming climate on the geographical distribution of this pest might be low due to other biotic and abiotic factors.. With reference to the increased potential for development, a modest increase in those areas where this pest has already been reported was estimated: these are areas already characterized by high temperatures and the warming climate could represent a more stressful environmental condition for the MCB, leading to not substantial modifications in the phenological development or even to a worsening. The results of this work suggest to further investigate which are the other factors that control the MCB distribution range: this would allow more specific estimates of the potential distribution and development of the MCB in Europe, and consequently of the potential damage to maize crops. Thanks to the implementation technology used for developing the modelling approaches presented in this paper, such improvement can be easily implemented and integrated.

3.2. Comparison between two different methods for predicting the peak of adult flight of insect borers

This work was published in the ISI journal International Journal of Biotmeteorology. Complete reference is: Maiorano 2012, A physiologically based approach for degree-day calculation in pest phenology models: the case of the European Corn Borer (Ostrinia nubilalis Hbn.) in Northern Italy, Int J Biometeor 56(4):653-659). Here follows the abstract of the work.

3.2.1. Abstract

Phenological models based on degree-day accumulation have been developed to support the integrated pest management of many insects. Most of these models are based on linear relationships between temperature and development, and on daily time step simulations using daily minimum and maximum temperatures. This approach represents an approximation that does not take into account the insect physiological response to temperature, and daily temperature fluctuations. The objective of this work has been to develop a phenological model for the European corn borer (ECB) based on the insect physiological response to temperature and running at an hourly time step. Two modeling solutions based on the same generic compartmental system have been compared: the first based on a physiologically based relationship between temperature and development, and using hourly derived temperatures as input (HNL modeling solution); and the second based on a linear relationship between temperature and degree-day accumulation and using daily temperature (DL modeling solution). The two approaches have been compared using ECB moth capture data from the Piemonte region in Northern Italy. The HNL modeling solution showed the best results for all the accuracy indicators. The DL modeling solution showed a tendency to anticipate ECB phenological development too early. This tendency is attributable to the linear relationship between temperature and development, which does not take into account (1) the decline of this relationship at high temperatures, and (2) the daily fluctuation of temperature. As a consequence, degree-days accumulation is accelerated in the DL modeling solution and the phenological development anticipated.

3.3. Comparison between different methods for simulating and mapping the potential distribution if insect borers

This work was published in the ISI journal Ecological Modelling. Complete reference is: Maiorano, Bregaglio, Donatelli, Fumagalli, Zucchini, 2012. Comparison of modelling approaches to simulate the phenology of the European corn borer under future climate scenarios, Ecol Model 245: 65-74. Here follows the abstract of the work.

3.3.1. Abstract

The phenological development of insects is simulated predominantly via models based on the response of the organisms to air temperature. Despite of a large body of literature supporting the evidence that the organism physiological response to temperature is nonlinear, including a declining phase, most of these models calculate the rate of development using a linear approach, implying that air temperatures mostly does not fall outside of the linear region of response to temperature of the organism. Another simplification is represented by the calculation of the rate of development using daily mean air temperature, which has already been demonstrated being a reliable method only in limited conditions. It can be hypothesized that the use of developmental models based on linear developmental rates, which can be successfully applied under climate conditions to which organisms are well adapted, could be inadequate under either future climatic scenarios or when extreme events occur (e.g., heat waves). In such contexts, linear responses might lead to interpretations of climate effects not consistent with the real organism physiological response to temperature.

In this work the case of Ostrinia nubilalis Hübner (European corn borer, ECB) development was taken as an example to compare (i) a nonlinear approach with hourly air temperature as input (HNL approach), (ii) a linear based approach with hourly air temperature as input (HL approach), (iii) a linear based approach with daily air temperature as input (averaging method, DL approach), and (iv) a linear based approach using a cutoff temperature with daily air temperature as input (DLcutoff approach). The comparison was performed under the IPCC (Intergovernmental Panel for Climate Change) emission scenario A1B, and three time frames in Europe: 1995–2004 (baseline–2000s), 2015–2024 (2020s), and 2045–2054 (2050s). The SRES A1B was selected as one of those for which the projected raise of temperature is estimated to be one of the highest, although the projected difference comparing to the other SRES is estimated as evident in the 2050s time frame, among the ones considered.

Using degree-days as a proxy for the rate of development, results showed that the DL approach predicts more than the HNL in all the time frames in almost all Europe with the exception of Southern Italy and the Mediterranean coasts of France and Spain where the differences were negligible. These effects were due (i) to the linear relationship used by the DL approach, and partially (ii) to the averaging operation that decrease the effects of high temperatures in regions with high (but not extreme) warm temperatures. The HNL and HL approach predicted the same pattern of degree-days accumulation in all Europe with the exception of the regions of Southern Iberian peninsula (across all the timeframes), Balkans, and Turkey (under the 2050 scenario). This effect was due to the different HNL and HL accumulation of degree-days at temperatures higher than the ECB optimum temperature. The comparison between the DLcutoff and the HNL approaches showed similar results to the DL vs HNL approach in central and Northern Europe, while in Southern Europe a negative difference (more DD accumulated for the HNL approach) were observed: in regions characterized by high temperatures, the cutoff temperature, setting a limit to the maximum temperatures diminished the calculated average temperature and as a consequence the calculated degree-days.

The results of this work showed that according to the method chosen for simulations, different results can be obtained, hence leading to different conclusions about the effect of a warming climate on pest development. These results stress the need of reconsidering the appropriateness of

models to be used, which cannot be assumed as correct on the basis of their effectiveness under current conditions.

3.4. Distribution of the potential risk of mycotoxins in grain maize kernels in Europe under climate change scenario

3.4.1. Introduction

The motivation of this study has been the lack of information on vulnerabilities and risks related to mycotoxin contamination in grain maize kernels in Europe under a changing climate in the next decades. The effect of climate change on the colonization by moulds and production of mycotoxins should be evaluated on a case-by-case basis since every mould species has its own optimum conditions of temperature and water activity for growth and formation of toxic metabolites (Miraglia et al. 2009). The project MIMYCS tries to answer to the need of evaluating the potential impact of climate variability on mycotoxin contamination taking into account the complexity of the system leading to mycotoxin contamination and the differences between toxigenic fungi. The analysis of vulnerability conducted in this study provides an indication of which regions may expect potentially significant contamination changes by the time horizon 2050.

3.4.2. Methods

An impact assessment of climate change scenarios on grain maize mycotoxin contamination was run covering maize areas in EU27, being centred on time horizon centred on the year 2050 (sample of 10 years), in comparison to the baseline centred on the year 2000 (sample of 10 years). One realization of the Intergovernmental Panel of Climate Change (IPCC) was used as the input of the analysis, based upon emission scenario A1B (i.e. scenario of a more integrated world with a balanced emphasis on all energy sources) form the runs of the global circulation model HadCM3 bias-corrected and downscaled from the original ENSEMBLE data set by the same regional climate model to a 25 km grid resolution.

The analysis was run on the three main fungi infecting maize and contaminating kernels with mycotoxins: *Fusarium verticillioides* (producer of fumonisins), *Fusarium graminearum* (producer of deoxynivalenol), and *Aspergillus flavus* (producer of aflatoxins). In this study adaption measures were not considered in the model simulations. Results refer to the simulation of abstractions of current agricultural systems under scenarios of climate change. In this work, current European maize agricultural systems of the different maize areas of Europe have been applied considering three factors: genotype (duration of crop cycle and of the different phenological phases), planting time, and harvest time. For this work, the same maize agricultural management parameterization used for the project AVEMAC (Donatelli et al. 2012b) was used.

3.4.3. Results and discussion

Results of simulations are shown in Figure 26. Maps are shown in terms of differences (%) between the baseline (centred on 2000) and the scenario centred on 2050. It must be pointed out that even if results are shown at the grid level (25 x 25 km^{-2}) the aim of this kind of analysis is to evidence general patterns of contaminations at the regional level. In fact, agricultural management inputs for simulations and outputs are abstracted at the level of grid, hence summarizing a range of possible production systems and contexts that are not possible take into consideration in detail.

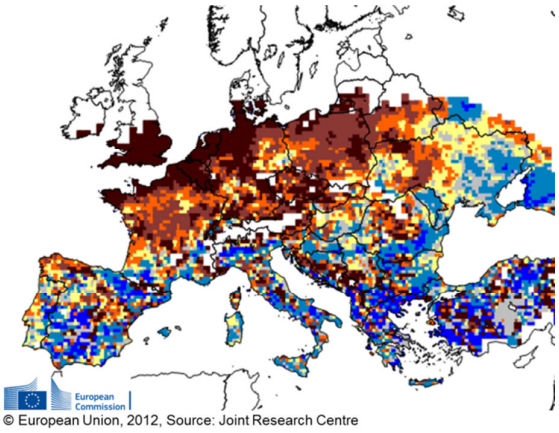


Figure 26a – Fumonisins by *Fusarium verticillioides*

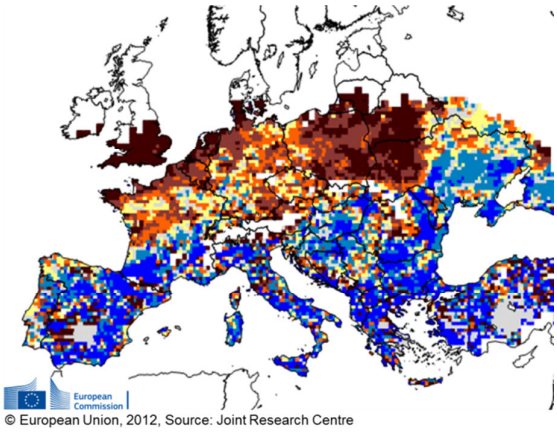
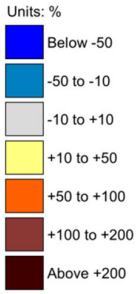


Figure 26b – Deoxynivalenol by *Fusarium graminearum*



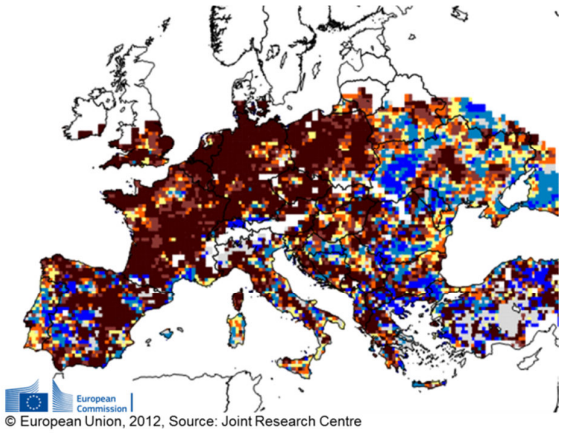


Figure 26c – Aflatoxins by *Aspergillus flavus*

Figure 26. Difference in the estimated contamination of maize grain kernels by fumonisins (25a), deoxynivalenol (25b), and aflatoxins (25c)

The Simulations gave different results according to the fungus taken into consideration. Simulations related to *Fusarium verticillioides* (Figure 26a), producer of fumonisins, showed that fumonisin contamination is expected to decrease in all the areas where currently these toxins are of great concern for maize producers. These areas include all the regions of Southern Europe where high contaminations of fumonisins are usually registered (Bottalico et al. 1989; Visconti et al. 1995; Logrieco et al. 2003). On the contrary, an increase of fumonisin contamination is expected in the maize areas of Northern Europe where contamination are low or sporadic. These results, and the knowledge of the actual distribution of this fungus and fumonisin contamination, suggest that actual climate conditions in Southern Europe represent an optimum condition for the development of this fungus and for fumonisin contamination. Results suggest that the expected future temperature increase will shift temperatures to a stressful range for the development of this fungus which will find better conditions in Northern European countries.

Simulations related to Fusarium graminearum (Figure 26b), producer of deoxynivalenol, showed a pattern of modification of the contamination similar to the one observed for fumonisins but more marked. This fungus has its optimal condition of growth and toxin synthesis at cooler temperatures that *F. verticillioides*. In fact usually it is not usual to observe high contamination by deoxynivalenol in maize kernels in Southern Europe: they are observed in wet and cool years, or in long cycle hybrids terminating their cycles during the cooler season. This toxin is more common in maize cultivated in Northern Europe. Results of simulations suggest that due to the increased future temperatures, deoxynivalenol contamination in Northern Europe will be further increased while it should no more represent a problem in Southern Europe.

Simulations related to *Aspergillus flavus* (Figure 26c), producer of aflatoxins, are quite different from the ones of the other two fungi. According to results of simulations, aflatoxin contamination is expected to increase in all Europe with the exception of some regions including Romania, Hungary, and Northern Greece. This fungus is common of warm and dry regions and important contamination by aflatoxins are reported in Southern Europe only in years (e.g. 2003) with these characteristics. This fungus is also characterize by a larger range of response to temperature (from 10°C to 47°C) if compared to the other two fungi with an optimum around 35°C. These characteristics explain why an increase of the risk related to aflatoxin contamination is expected in all Europe: differently from *F. graminearum* and *F. verticillioides*, any increment of temperature leading air temperature around 35° will represent a better conditions for this fungus and for aflatoxin contamination. On the contrary, the expected lower contamination in some regions of Romania, Hungary, Northern Greece, North Eastern Italy, and Central Spain, are probably due to the expected increased precipitations (Donatelli et al. 2012b) during summer season that could interfere with the dispersion of inoculum of this fungus (see Section 1, paragraph 1.2).

Section 4. TRAINING ACTIVITIES

Abstract

The MIMYCS project has included different training activities that have significantly increased my scientific and complementary knowledge, skills, and expertise. These training activities most probably will have a strong impact on my career as an independent researcher as this new knowledge will have an impact on the new project that I will develop. In this section, a brief description of all the training activities followed at the JRC is given.

4.1. MIMYCS training activities

4.1.1. Process-based modelling and biophysical model development

This training was given by Dr. Marcello Donatelli and has been conducted through a training-through-research approach. Dr. Donatelli has more than 25 years of experience in model development. Training has been conducted through the development of the project following progressive steps of complexity, from the development of simple models to their integrations in more complex models and finally to the development of a complex frameworks of models (MIMYCS) integrating all the developed models. Training has also included the testing and calibration of models, and their use for analysis under different climate variability scenarios.

4.1.2. Object oriented and component oriented programming with C#

This training was given in two main steps. The first step training was given by Dr. Donatelli through a training-through-research approach during the implementation of the first model components. First step included: (i) basis of programming language C# and the programming environment Visual Studio, (ii) development of model software components following the component-oriented programming paradigm, (iii) basis of object-oriented programming.

The second step included an intensive course of 5 days about C# and Object Design followed during the last semester of the project in order to maximize my new programming skills.

The course was followed at the JRC and it was organized by Valtech Training.

Program of the course included:

- Fundamental object technology concepts
- Introduction to C# and .NET Technologies
- Class definition in C#
- C# syntax
- Containment
- Arrays
- Namespaces
- Process and requirement analysis
- Domain models
- Designing with GRASP patterns
- Collaboration diagrams UML
- Creating design class diagrams
- Mapping design artifacts to code
- Interfaces
- Collections
- Generalization, specialization, inheritance, polymorphism
- Exception handling
- Input and output Streams

4.1.3. Insect pest population dynamics

During the development of MIMYCS, in order to improve my knowledge on insect pest development, I followed a short training given by Prof. J. Baumgärtner (now retired) of the University of Milan about Insect pest population dynamics. As a consequence of the training, a preliminary study was conducted for the development of a tool for the simulation of the population dynamics of the European Corn Borer. This work was presented as a poster presentation at the European Conference on Ecological Modelling. Complete reference is: Maiorano A., Rigamonti, I., Baumgärtner J., 2011. DDM-Sim 0.1: A generic software component for time varying distributed delay models with attritition. 7th European Conference on Ecological Modelling, 30 May – 2 June 2011, Riva del Garda, Italy

4.1.4. Writing of scientific papers

This training was done according to two approaches. The first approach included the writing and publication of two papers in collaboration with Dr. Donatelli. The second approach included the participation to a training course organized at the JRC about Scientific Writing. The course objectives included topic related to writing clearly, concisely and accurately on scientific topics, adopting an appropriate English style for scientific communications, formatting reports, posters, slides, and other documents, proofreading for correctness and consistency, increasing chances of publication in peer-reviewed scientific journals. The program of the course included:

- The writing process - and the elements of style: Introduction to the importance of technical and scientific writing
- Publish or perish: The importance of publishing your research. What can be published, and where?
- Materials and methods: a 'recipe' for the study. Preferred sequences for different kinds of research.
- Coping with complexity: Mind-mapping and other ways of organizing large volumes of information.
- Developing arguments throughout the paper: The difference between the introduction and the discussion
- Not just words: Principles of design and layout.
- Refining your style: Techniques for making writing 'flow' better.
- The finishing touches: Giving your paper a good title and effective abstract.

4.1.5. Project management

Project management training activities have included:

- Monitoring and supervision of the project “Analysis and evaluation of modelling preharvest quality for CGMS crops” developed by the University of Milan for the JRC. I was in charge with work progress monitoring and reporting, maintaining contacts with the researchers developing the project, checking and approval of deliverables.
- Training course about Project Management Fundamentals at the JRC, aimed at obtaining a solid understanding of project management skills, concept and techniques at each stage of a project life cycle, providing a solid foundation of project management terminology and techniques, how they are used to manage a project effectively during initialization, planning, execution, control and close.

Programme of the course included:

- Introduction to Project Management: Why Project Management, The Project life cycle, The nine knowledge areas
- Scope Management: Scope planning and definition, The work Breakdown Structure
- Time Management: Activity definition, Sequencing and estimating, Schedule development
- Cost Management: Resource planning process, Estimating methods and tools
- Quality Management: Concept of Quality Assurance and Quality Control
- Human Resource Management: Concept of Quality Assurance and Quality control
- Communications Management: Concepts of organisational planning and team development, Techniques of team management
- Procurement Management: Contract types
- Risk Management: Risk categories, Risk assessment and response planning
- Integration and Control Management: Overview of techniques, Tools and procedure to initiate, plan, execute, control and close the action.

4.1.6. Agrometeorological analysis and crop forecast, Crop Forecast Bulletin

AGRI4CAST Team has been developing and operationally running a crop yield forecasting system since 1992 in order to provide timely crop production forecasts at European level. On the basis of this system, training about agrometeorological analysis and crop forecast was given by Dr. Bettina Baruth in order to acquire new skills in agrometeorological analysis at regional, national and continental level in Europe. As a second step of this training I was involved in the crop forecast

analysis and in the writing of the MARS Bulletin (http://mars.jrc.ec.europa.eu/mars/About-us/AGRI4CAST/MARS-Bulletins-for-Europe) prepared for the European Commission.

4.1.7. ISO9001:2008 specifications for project management

This training was given as a training course aiming at acquiring knowledge about quality specifications in project management at the JRC.

The course programme included:

- Quality management principles
- Main requirements of the ISO9011:2008 standards
- Quality management structure in the JRC
- Future development of the Quality Management Structure at the JRC

4.1.8. English language course

During the first semester of the project an English course of 4 hours/week per 4 months to improve my language skills.

4.1.9. Writing of project proposal

This training activity was given through the preparation of a new project proposal which have been submitted at the end of August 2012. The project proposal has been submitted in the framework of the Marie Curie International Outgoing Fellowship Actions. The project proposal aims at deepening some skills and knowledge acquired during the development of MIMYCS such as the modelling of insect pest population dynamics.

Section 5. PROJECT MIMYCS RESULTS AND CONCLUSIONS

5.1. Project MIMYCS results

5.1.1. Scientific results

The project MIMYCS has included the development of a complex framework of models for the simulation of the system leading to mycotoxin contamination in grain maize in Europe. In this context, the main scientific obtained results are:

- Development of an original model for the simulation of moisture content in maize kernels during their development, maturation, and dry-down;
- Implementation and further development of a phenological model for the simulation of the European corn borer (*Ostrinia nubilalis*) and the Mediterranean corn borer (*Sesamia nonagrioides*);
- Development of an original model for simulating insect survival during the overwintering season (not included in the project proposal);
- Development of an original model for the simulation of fungi development, infection of maize grain, and mycotoxin synthesis;
- Integration of the MIMYCS framework in the BioMA platform of the European Commission

These objectives have been reached thanks to new skills on model software component development that have allowed:

- Implementation of the models in independent, reusable, and extensible software components;
- Development of a framework of model integrating the three models components above, implemented as an independent model software component that were included in the BioMA platform

The development of MIMYCS and related components, and their integration in the BioMA framework has allowed obtaining some scientific results that have been published in international publications or whose publications are in preparation. These results include:

- Simulations at EU scale of maize borers survival and phenological development and analysis of potential distribution under current climate conditions and under climate scenarios (published in international congress paper, see list of publications)
- Simulation at EU scale of mycotoxin contamination in maize grain and analysis of potential change in the risk of mycotoxin contamination in grain maize kernels in Europe current climate conditions and under climate scenarios (publication in preparation)
- Comparison of different methodologies to simulated insect pest phenological development under different climate scenarios (published in ISI journal)
- Comparison of different approaches for simulating the occurrence of adult flight peak of insect borers for pest management purposes (published in ISI journal)
- Simulation of moisture content in maize kernels during maturation (published in international conference paper)

5.1.2. Dissemination of scientific results of project MIMYCS

Publications in ISI journals

- **Maiorano A.**, Bregalio S, Donatelli M, Fumagalli D, Zucchini A, 2012. Comparison of modelling approaches to simulate the phenology of the European Corn Borer under future climate scenarios. Ecological Modelling, 245: 65-74
- **Maiorano A.** 2011. A physiologically based approach for degree-day calculation in pest phenology models: the case of the European CornBorer (Ostrinia nubilalis Hbn.) in Northern Italy. Int J Biometeorol, 56(4): 653-659

Publication in ISI journals (Currently in preparation)

- **Maiorano A.,** Donatelli M., 2012. Potential distribution and phenological development of the Mediterranean Corn Borer (Sesamia nonagrioides) under warming climate in Europe. To be submitted to Ecological Modelling
- **Maiorano A.,** Donatelli M., 2012. Modelling maize grain moisture content during maturation and post-maturity dry-down. To be submitted to Eruopean Journal of Agronomy

Publications in peer-reviewed papers at international conferences

- **Maiorano A.,** Bregaglio S., Donatelli M., 2012. Comparison of modelling approaches to simulate the phenology of agricultural insect pests under future climate scenarios. Congress of the European Society of Agronomy, 20-25 August 2012, Helsinki, Finland
- **Maiorano A.,** Fumagalli D., Donatelli M., 2012. Potential distribution and phenological development of the Mediterranean Corn Borer (Sesamia nonagrioides) under warming climate in Europe. Congress of the European Society of Agronomy, 20-25 August 2012, Helsinki, Finland
- **Maiorano A.,** Donatelli M., 2012. Modelling maize grain moisture content during maturation and post-maturity dry-down. Congress of the European Society of Agronomy, 20-25 August 2012, Helsinki, Finland
- **Maiorano A.,** Donatelli M., 2012. MIMYCS, A framework for simulating maize kernels mycotoxin contamination in Europe. Congress of the European Society of Agronomy, 20-25 August 2012, Helsinki, Finland
- **Maiorano A.,** Fumagalli D., Donatelli M., 2012. Potential distribution and phenological development of the Mediterranean Corn Borer Sesamia nonagrioides in Europe under warming climate. International Environmental Modelling and Software Society Congress, 1-5 July 2012, Leipzig, Germany
- **Maiorano A.,** MIMYCS – A framework for simulating maize kernels mycotoxin contamination in Europe. Marie Curie Researchers Symposium, 25-27 September 2011, Warsaw, Poland
- **Maiorano A.,** Bregaglio S., Fumagalli D., Donatelli M., Models for pest development simulation under climate scenarios. 7th European Conference on Ecological Modelling, 30 May – 2 June 2011, Riva del Garda, Italy
- **Maiorano A.,** Rigamonti I., Baumgartner J., DDM-Sim 0.1: A generic software component for time varying distributed delay models with attritition. 7th European Conference on Ecological Modelling, 30 May – 2 June 2011, Riva del Garda, Italy
- **Maiorano A.,** Donatelli M., Baruth B. 2010. Project MIMYCS: a simulation model system for simulating mycotoxin contamination in maize grain in Europe. XIth European Society of Agronomy Congress, 29 August – 3 September 2010, Montpellier, France

Contributed talks in international conferences

- "Potential distribution and phenological development of the Mediterranean Corn Borer (Sesamia nonagrioides) under warming climate in Europe" 6th International Environmental Modelling and Software Congress, Leipzig (Germany), July 2012
- "Comparison of modelling approaches to simulate the phenology of agricultural insect pests under future climate scenarios" 12th European Society of Agronomy Congress, Helsinki, Finland, August 2012

Web page

The project MIMYCS and its results will be soon made available to the public through the web site of the Joint Research Centre. A web page is already available containing the abstract of the project, but it will be soon integrated with new material. The webpage is at http://mars.jrc.ec.europa.eu/mars/Projects/MIMYCS.

5.1.3. Training activities results

Training activities have allowed:

- increasing my scientific knowledge on biophysical model development and analysis
- acquired new skills on the basic concepts of insect pest population dynamics
- acquiring new skills and competences on software development for implementing biophysical models
- acquiring new skills on agrometeorological analysis and crop forecast
- acquiring new skills on project management and quality requirements
- improving my Englush language skills

In particular, the complementary activity as agrometeorological analyst has allowed the participation in the following publications of the MARS Bulletin:

- B. Baruth, [...], A. Maiorano, [...], August 2012. MARS Bulletin August, Vol 20, No 8
- B. Baruth, [...], A. Maiorano, [...], July 2012. MARS Bulletin July, 20, No 7
- B. Baruth, [...], A. Maiorano, [...], June 2012. MARS Bulletin June, Vol 20, No 6
- B. Baruth, [...], A. Maiorano, [...], May 2012. MARS Bulletin May, Vol 20, No 5
- B. Baruth, [...], A. Maiorano, [...], April 2012. MARS Bulletin April, Vol 20, No 4
- B. Baruth, [...], A. Maiorano, [...], March 2012. MARS Bulletin March, Vol 20, No 3
- B. Baruth, [...], A. Maiorano, [...], February 2012. MARS Bulletin Febraury, Vol 20, No 2
- B. Baruth, [...], A. Maiorano, [...], January 2012. MARS Bulletin January, Vol 20, No 1

5.1.4. Additional Links with other Research Centres and Industry

The development of the project MIMYCS gave me the opportunity to enter in contact with the Canadian Forest Service in Canada and with the private company Syngenta in Italy.

I entered in contact with Dr. Jacques Regniérè of the Canadian Forest Service during the training activity related to Writing of project proposal (see 0, paragraph 4.1.9). In fact the Marie Curie IOF proposal was written in collaboration with him for the outgoing phase, for his expertise on insect pest population dynamics modelling, and Dr Marcello Donatelli for the return phase of the project.

I entered in contact with Syngenta Italy thanks to their interest in the development of the models of the framework MIMYCS. Thanks to their interest in the project a collaboration agreement was signed between Syngenta and the JRC to collaborate on the further development of the MIMYCS framework for pest management purposes (Agreement number 32773, Ref. Ares(2012)306221 – 15/03/2012). On the basis of the collaboration agreement, they are providing data about maize insect pest development in Northern Italy, moisture content in maize kernels during development, and they will provide data about mycotoxin contamination in maize kernels from experimental fields in Northern Italy since 2004. At the moment it is under discussion the possibility to work also on data coming from experimental fields in Spain and France.

5.1.5. Not reached objectives

Two objectives have not been reached:

1) Sensitivity analysis of MIMYCS model framework, and
2) Validation of MIMYCS using data provided by extension services in Spain, France and Italy and presentation of results.

Sensitivity analysis issues

It was not possible to conduct a sensitivity analysis on the MIMYCS model framework and on its components as the development of the tool for doing it (LUISA - http://agsys.cra-cin.it/tools/luisa/help/) has been delayed and it still has not been integrated in the BioMA platform. Nevertheless, the software interface for using LUISA with MIMYCS has already been developed. Thus, as soon as LUISA will be ready and integrated into BioMA sensitivity analysis will be conducted and results published (for more information about LUISA development please contact Dr Marcello Donatelli: marcello.donatelli@jrc.ec.europa.eu).

Validation issues

Data from France: The project proposal included a collaboration with the French extension service ARVALIS who should have supported the project with agronomic and mycotoxin contamination data to validate the MIMYCS model framework. While during the project proposal preparation ARVALIS assured their support, during the development of the project they have changed their position and they did not support the MIMYCS project. The reason for this change of position is that since they are economically supported by French agricultural producer associations, they were afraid that the results of the project MIMYCS might lead to publications which include maps of mycotoxin risks across Europe, including France, that might provoke their financial supporter's disappointment.

Data from Spain and Italy: The data provided by the Spanish and the Italian extension services were considered not adequate to test a so complex model like MIMYCS. In fact, provided data came from samples collected in farm maize field, with no replications, in most cases without following an adequate sampling methodology, with samples analysed using different lab methodologies. Further, a sampling problem become evident: samples coming from the same location and from the same or very similar agro-climatic conditions showed a very high variability in mycotoxin contamination. Consequently MIMYCS was not tested against observed mycotoxin contamination. For this reason, the meeting included in the project proposal to show them the results of the project has been postponed. Nevertheless, due to the interest of the private company Syngenta and to the collaboration agreement with them (see this Section, paragraph 5.1.4), data about mycotoxin contamination since 2004 coming from different experimental fields in Northern Italy will be made soon available for testing and calibrating MIMYCS. The meeting with the extension services will be re-organized after these data will be used for calibrating and validating MIMYCS.

5.2. Conclusions

The MIMYCS project has led to the development of a framework of models for the simulation of mycotoxin synthesis in grain maize kernels during the cultivation phase. This is to be considered the first version of a framework which has been thought to be evolved and further improved in the close future. Thanks to the technology used for developing it, the further improvement of the MIMYCS framework and of all its components, the development and integration of new components, their testing and validation will be simple even considering the complexity of the framework. The main result of the project is the development of a framework of model which will allow an easy re-use of it for performing simulations (i) to inform European policy makers involved in food and feed safety of the effects of European mycotoxin policies and help them to fix safe and, at the same time, feasible contamination limits, (ii) to assess about climate change scenario effects on the pathosystem and on future maize-based food and feed products safety, (iii) to assist maize producers in controlling mycotoxin contamination through agro-management and improving maize grain safety. In particular, the collaboration with the Joint Research Centre has allowed the integration of MIMYCS in the BioMA framework used by the European Commission for impact studies on agriculture related to weather and agricultural management: the integration in the BioMA framework will increase the possibility that it will become an instrument used for policy purposes at the European level.

The training activity included in the project MIMYCS gave me the possibility to deepen my scientific knowledge, to acquire new skills on new technologies and on new research and management methodologies. These new knowledge and skills have the potential to give an acceleration to my research career in an international context.

Section 6. REFERENCES

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Abstract

Mycotoxins are toxic compounds, produced by fungi and recognized as the main cause of chronic intoxications in the world. Maize is one of the crops subjected to the most critical mycotoxin problems throughout the world. Mycotoxin contamination in maize grain is the result of a complex plant pathosystem composed of maize plants, toxigenic fungi and insect borers. Warming of the climate system could have an important impact on the system, leading to mycotoxin contamination in grain maize and the potential effects are very difficult to foresee. The project MIMYCS has aimed at the development of a simulation model system to simulate at EU scale mycotoxin contamination in maize grain in different climatic, environmental and agro-management situations. The MIMYCS model system has been developed as composed by three main model components: i) MIMYCS.Maize, which integrates the crop model CropSyst and simulates maize phenological development and moisture in kernels during their development and maturation, ii) MIMYCS.Borers simulating two maize borers (Ostrinia nubilalis and Sesamia nonagrioides) phenological development and their damage to the ear, enhancing fungi growth and development, iii) MIMYCS.Fungi simulating fungi development and their interactions, using information received from Maize and the Borers modules. Finally, the MIMYCS simulation system, can quantify the risk of mycotoxin (aflatoxins, fumonisins, deoxynivalenol) contamination in maize grain. As a first application, MIMYCS has been used to predict and evaluate the effect of climate change on maize grain mycotoxin contamination in Europe. Future applications of MIMYCS will include its use as a decision support system to manage mycotoxin contamination during the field phase.

During the development of the project training activity have included: i) process-based modelling and biophysical model framework development, ii) basic concepts of insect pest population dynamics modelling iii) object-oriented and component-oriented programming with C#, iv) writing of scientific papers, v) project management, vi) agrometeorological analysis and crop forecast, vii) writing of project proposals

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