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Potential distribution and phenological development of the Mediterranean Corn Borer (*Sesamia nonagrioides*) under warming climate in Europe

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Abstract: Climate change has the potential to modify the current distribution and phenological development of insect pests. Using a generic phenological model coupled to a model to simulate potential mortality during the overwintering season, we analysed the potential distribution and phenological development of the Mediterranean Corn Borer (MCB) *Sesamia nonagrioides*, under simulated warming climate at three time horizons (Baseline, 2030s, 2050s) in Europe. The mortality model included the simulation of larvae survival in the roots under the soil surface, thus simulating temperature of the soil of a maize field. Results of survival estimate showed that mortality does not decrease noticeably spreading MCB in currently cold areas where it has never been reported, due to the potential survival already assured by the fraction of diapausing larvae in the roots. These results indicate that low temperatures affecting overwinter survival might not be the most important limiting factor determining MCB distribution. The development model linked to the estimate of survival including larvae diapausing in the soil showed a potential increase of generations in the Balkans and Turkey, and, to a more limited extent, in Germany. On the contrary, the estimated increase is negligible in the Mediterranean basin, due to the potential stressful effects of high temperatures. The models were implemented in a software component (MIMYCS.Borers) composed of discrete model units. This is one of the models of the framework MIMYCS for the simulation of mycotoxin contamination in grain maize. The component based software implementation can be easily re-used in any framework based on the Microsoft .NET platform, and it was used in the BioMA platform of the European Commission.

Keywords: *Sesamia nonagrioides*, potential distribution, phenological development, climate change, BioMA, MIMYCS

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.

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. Bayram et al. [2007] 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 Mediterranean basin, (up to 4 generations per year), and of the Atlantic coasts up to the French coasts of the western Loire region (1 or 2 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, linking 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.

2 MATERIALS AND METHODS

The work was carried out in four phases: a) formalization and development of a winter survival model; b) parameterization of a temperature-based phenological model; c) implementation of the biophysical models in software model components; and d) application of the models in spatialized simulation runs to test MCB survival and development in Europe under future scenarios and baseline weather.

2.1 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 $\leq -2^\circ\text{C}$, 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 (M_{int} , %). Probit analysis was performed for estimating the lethal time (hours) for 90% of mortality (LT_{90}) at the tested sub-zero temperatures. Following results of probit analysis, a thermal death time curve (TDTC) representing LT_{90} at any temperature $\leq -2^\circ\text{C}$ was determined. Mortality (%) at any temperature $\leq -2^\circ\text{C}$ 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 LT_{90} (pLT_{90} – equal to the actual time exposure divided by LT_{90}), and the proportion of actual mortality (pM_{90} – equal to the actual mortality divided by 90%). The proportion of 90% mortality was calculated using the logarithmic function:

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

where a and b are fitting parameters obtained by optimizing eq. (1) to the observed pM_{90} 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 $M_{max}/90$ which is the proportion of maximum mortality ($M_{max}=100$), that is equal to 1.11. Finally, actual mortality (M_i , %) is calculated as the product of 90% per pM_{90} . Thus, at each time step i during diapause, if hourly temperature is $\leq -2^\circ\text{C}$, the rate mortality M_i is calculated and the following rule is applied:

$$\text{if } M_i > (S_0 - S_{i-1}), \quad \text{then } S_i = S_0 - M_i, \quad \text{else } S_i = S_{i-1} \quad (2)$$

where S_0 is the relative starting level of population (given by $100 - M_{int}$, %), S_i are actual survivors, and S_{i-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 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 $\geq 10\%$.

2.2 Phenological model

The data source used for the developmental model consisted of mean development time (days) of immature stages of MCB at constant temperatures found in Hilal [1981], López et al. [2001], and Fantinou and Chourdas [2005], while data found in Fantinou et al. [2004] were used to determine the time needed to complete the pre-oviposition period of the adult stage.

The phenological model uses the rate summation method which is based on the concept that development rates are additive for changing temperatures, and it uses as the development rate the reciprocal of the mean development time for each constant temperature. Development rates for completing the different stages were normalized by dividing the observed response to a given temperature by the maximum developmental rate in order to obtain a common temperature response profile for all the stages. In this way, multiplying the reciprocal of the days required to complete a generation at the optimum temperature, the rate summation at any instant is the fraction of the mean process time completed at that instant.

Differently from other works where the development of maize insect borers was simulated using a linear response to temperature, in this work a non-linear response was chosen to properly account for above optimum temperatures. Non-linear response model must be preferred whenever simulations must cover temperatures over the full range of physiological activity, as in the case of studies under warming climate. The following beta function by Yan and Hunt [1999] was used to fit the normalized developmental rates:

$$f(T) = \left(\left(\frac{T(h) - T_{min}}{T_{opt} - T_{min}} \right) \left(\frac{T_{max} - T(h)}{T_{max} - T_{opt}} \right)^{\left(\frac{T_{max} - T_{opt}}{T_{opt} - T_{min}} \right)^c} \right)^c \quad (3)$$

where $T(h)$ is the hourly temperature, T_{min} is the minimum extreme temperature for development, T_{max} is the maximum extreme temperature for development, T_{opt} is the optimum temperature of development, and c is the shape parameter. Parameters T_{min} , T_{opt} and c were optimized to fit the normalized developmental rates (least squares method, Microsoft Excel Solver). Since experimental data within the feasible temperature range for T_{max} were not found available in literature, the constraint imposed to the optimization was setting T_{max} to the value of 40°C, based on the values estimated by López et al. [2001]. The phenological model was started after that scotophase (dark phase of photoperiod) including civil twilight, was <12h [Eizaguirre et al. 2008]. Scotophase was estimated using the SolarRadiation model component (<http://agsys.cra-cin.it/tools/>) with latitude and day of year as input.

2.3 Model implementation

The models were implemented in the software model component MIMYCS.Borers, composed of discrete model units of fine granularity. This is one of the models of the framework MIMYCS (Maize Infection and MYcotoxin contamination Simulator - FP7 Marie Curie Project) being developed at the European Commission for the simulation of mycotoxin contamination in grain maize. Models of the MIMYCS framework are developed using the software component oriented paradigm which allow the reusability of them either as standalone models, or composed with other models for the development of new modelling solutions. The component architecture was the one proposed by Donatelli and Rizzoli [2008]. The MIMYCS components can be easily re-used in any platform based on Microsoft .NET platform and they are currently being implemented as modelling solutions for the BioMA platform of the European Commission (<http://bioma.jrc.ec.europa.eu/>).

2.4 Spatialized simulation runs and 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. 2012], 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 centred on the year 2000, and the IPCC emission scenario A1B centred on 2030 and 2050. The realization of the A1B scenario originated from runs of the ECHAM5-R3 global circulation model coupled to the HIRHAM5 RCM for the downscaling. The aim was to estimate potential distribution and development in the future temperature regime compared to current conditions.

3 RESULTS AND DISCUSSION

Figure 1 and Figure 2 show the thermal death time curve for 90% mortality and the curve of proportion of 90% mortality used in the survival model.

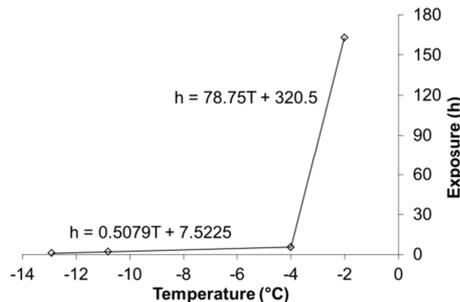


Figure 1. Thermal death time curve indicating the required exposure to cause 90% of mortality

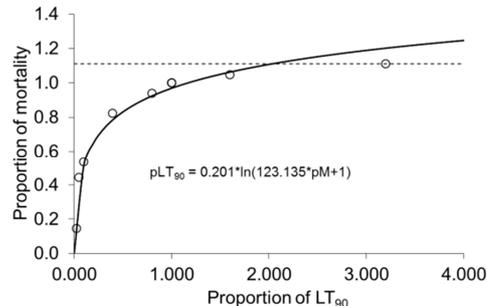


Figure 2. Mortality as a function of proportion of time for 90% mortality (LT_{90}). Dotted line is the maximum proportion of mortality

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

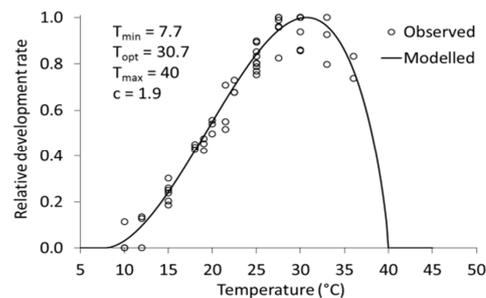


Figure 3. Observed normalized growth rates of MCB and estimated model parameters

temperatures, but the formation of ice can cause damaging deformation to cells [Mazur 1984].

Developmental rates are shown in Figure 3 together with the modelled response and estimated parameters. Total number of days required to complete one generation at the optimum temperature resulted equals to 40 days which means a relative growth rate of 0.025 d^{-1} .

3.1 *Sesamia nonagrioides* survival

Results of MCB simulated survival potential across Europe are showed in Figure 4a and 4b (AirMS results), and 4c and 4d (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 affected by MCB potential survival under the baseline: the AirMS estimates a potential distribution which is much more limited compared to the SoilAirMS.

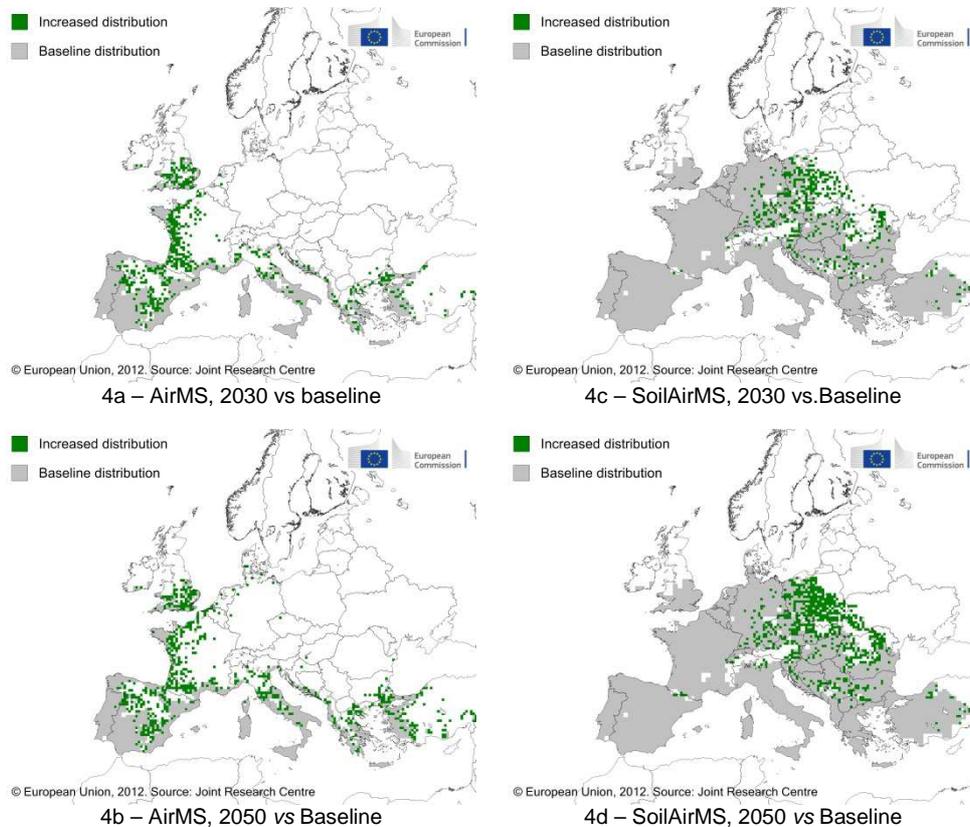


Figure 4. Difference in the estimated potential distribution between baseline (grey) and 2030-2050 scenarios (green) estimated by AirMS (air temperature as input, 4a-4b), and SoilAirMS (soil and air temperature as input, 4c-4d).

The potential distribution estimated by AirMS includes mainly the Mediterranean and Atlantic coastal regions of Europe, which are already known from literature as 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.

The results coming from the SoilAirMS approach are more interesting as the formulation of this model more closely represents the real system compared to the AirMS. In fact, 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]. Noticeably, the results coming from this approach

show a completely different picture, extending the estimated potential distribution of the MCB to almost all the areas of Europe where maize is cultivated, including areas of Northern Europe where the presence has never been reported.

The model AirMS, not considering the role of soil temperature, but only the colder and more limiting air temperature, possibly indicates areas with a stronger pressure of the MCB due to the survival guaranteed also by the fraction of larvae out of the soil. At the same time, this selection leads to an estimate of the distribution which is more restrictive than the one reported in literature. Instead, the SoilAirMS estimates, which include all the areas where the presence of the MCB has been monitored, shows that air temperature does not explain, as unique factor, the actual distribution of the MCB.

However, the SoilAirMS estimates the presence of the MCB also in areas where it has not been found, suggesting that other biotic or abiotic factors than temperature could be more important than the temperature itself in restricting the MCB distribution. These factors might include i) a high percentage of larval population whose development is anticipated compared to the diapause induction signal of the critical photoperiod, and that consequently continue development exposing 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]. Another possible source of uncertainty is 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.

One possible source of uncertainty of the SoilAirMS model is the proportion of population overwintering in the soil and subjected to soil temperature which have been generalized and fixed at a certain level (80%). This percentage is likely not a constant, but it is not modelled. Nevertheless, even considering this source of uncertainty, the MCB distribution simulated by SoilAirMS must be considered closer to reality than AirMS in modelling the response to temperature of the MCB as the model formulation is closer to reality according to literature.

For what concerns the estimated increase in potential geographical distribution, Figure 4 shows that in both cases the potential distribution of MCB is expected to increase under 2030 and 2050, but the main increase is expected under 2030 scenario.

3.2 *Sesamia nonagrioides* 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.

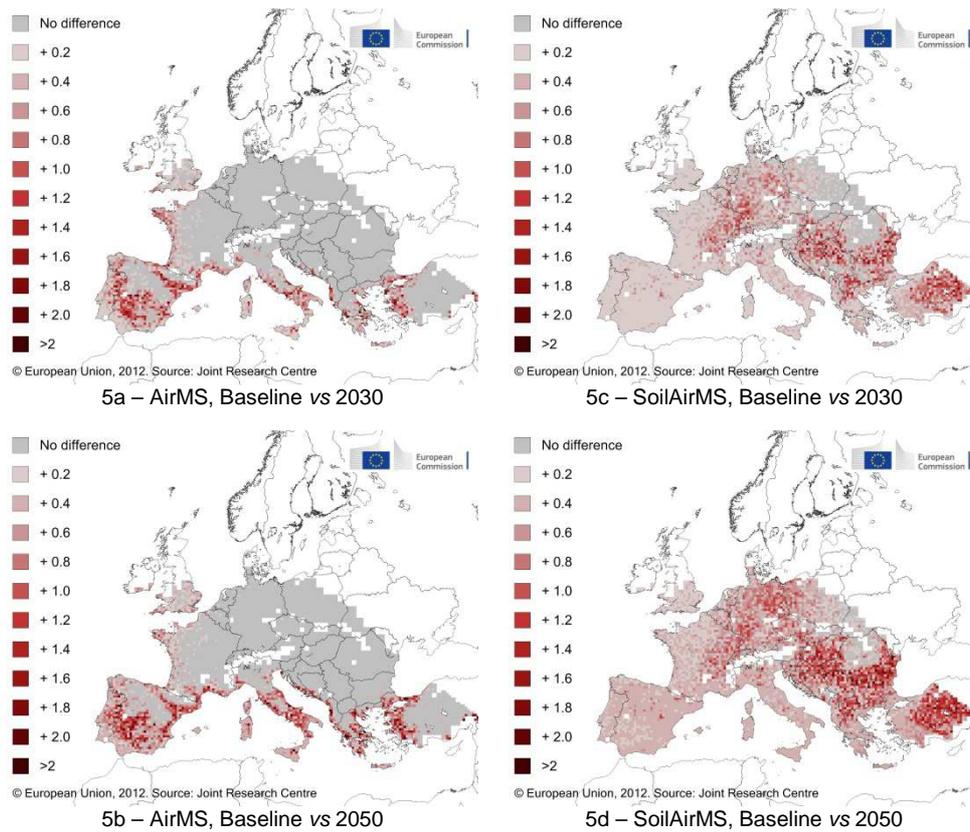


Figure 5. Differences in the potential number of generation between baseline and 2030-2050 scenarios according to AirMS (5a-5b) and SoilAirMS (5c-5d)

4 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 direct effects 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.

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