

PESTS OCCURRENCE MODEL IN CURRENT CLIMATE – VALIDATION STUDY FOR EUROPEAN DOMAIN

Eva Svobodová, Miroslav Trnka, Martin Dubrovský, Daniela Semerádová,
Josef Eitzinger, Zdeněk Žalud, Petr Štěpánek

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Abstract

SVOBODOVÁ EVA, TRNKA MIROSLAV, DUBROVSKÝ MARTIN, SEMERÁDOVÁ DANIELA, EITZINGER JOSEF, ŽALUD ZDENĚK, ŠTĚPÁNEK PETR: *Pest occurrence model in current climate – validation study for European domain*. Acta Universitatis Agriculturae et Silviculturae Mendelianae Brunensis, 2013, LXI, No. 1, pp. 205–214

The present study yields detail validation of the pest occurrence models under current climate in wide European domain. Study organisms involve *Cydia pomonella*, *Lobesia botrana*, *Ostrinia nubilalis*, *Leptinotarsa decemlineata*, *Oulema melanopus*, *Rhopalosiphum padi*, and *Sitobion avenae*. Method used in this study belongs to the category climate matching (CLIMEX model) allowing the estimation of areas climatically favourable for species persistence based on the climatic parameters characterising the species development. In the process of model validation parameters were iteratively tested and altered to truly describe the pest presence. The modelled pests presence was verified by comparison of the observed pests occurrence with the number of generations in given modelled area. The notable component of the model parameterization was the sensitivity analyses testing the reaction of species development on changing meteorological items. Parameterization of the factors causing distribution patterns of study species was successful and modelled potential distributions of species correspond well to known core distribution areas for all of these species. This validation study is intended as an initial for forthcoming studies focused on the estimation of geographical shifts of selected pests in the conditions of climate change within the Europe.

climate change, climate matching, pests, endangered areas, northern range, CLIMEX

Productivity of crops grown for human consumption is at risk due to the incidence of pests, especially weeds, pathogens and animal pests, for instance without crop protection almost 75% of attainable potato production would be lost to pests (OERKE, 2006). Pest life cycles are affected by various factors, among which climate conditions are the most significant. Climate can limit the distribution of a species directly by influencing survival and fecundity or indirectly through its effects on interacting species, including food sources, natural enemies and competitors (GASTON, 2003). Under current climate conditions, insect species diversity per area tends to decrease with increasing latitude. A similar trend is usually seen with increasing altitude (GASTON, WILLIAMS, 1996).

The present validation study represents the base material for forthcoming studies estimating the occurrence area of selected pests in the conditions of climate change. Projected studies will focused on the geographical shift of species northern range and determination of areas the most endangered by newly species establishment. Warmer conditions of climate change may be expected to promote pole ward extension of the ranges of species that are currently limited by low temperature. Changes in climate may result in alterations in the geographical distribution of the species, increased overwintering, changes in population growth rates, increases in the number of generations, extension of the development season, changes in crop-pest synchrony, changes in interspecific interactions,

and increased risk of invasion by migrant pests (PORTER *et al.*, 1991). An increase in the number of generations means an increase in the number of reproductive events per year. If the mortality per generation does not change, then the population of thermophile insects will potentially become larger under global warming (YAMAMURA, YOKOZAWA, 2002). This fact could play an important role in the case of multivoltine species. Most of these species are expected to widen their infestation area to higher latitudes and altitudes, as has been seen for butterflies (POLLARD *et al.*, 1995; HILL *et al.*, 2002). A higher survival rate during the overwintering period could result in an increase in the overwintering population and a consequent abundance of insects on crops in the summer. At the same time, the increasing temperature could likely support the earlier diapause termination of overwintering species, which will consequently appear earlier. This will influence the intensity of crop-insect interactions (YAMAMURA, YOKOZAWA, 2002). The impacts of climate change on pest populations in the northern hemisphere will differ according to the current geographical positions of populations within each species' current range. In the northern hemisphere, populations occurring toward the northern margin of a species' range will be subject to greater climatic stresses than those occupying more central regions, and therefore are expected to be less stable. In other words, organisms near the limits of their ranges are typically most sensitive to change (ARCHER, 1994).

Present study used the climate matching as a method for the assessment of regions climatically favourable for pests survival. Modelling the life stages of insect species is most often done through the accumulated degree-days method, while so-called climate matching is a common modelling tool for estimating the impact of climate change on the species' extension. Climate matching identifies extralimital locations that could be colonised by a potential invasive species on the basis of similarity to climates found in the species' native range (RODDA *et al.*, 2007). Several models that belong to the group of climate matching tools have been developed and applied in the past. Detail list of several models that belong to the group of climate matching tools is approachable in HEIKKINEN *et al.* (2006). Mechanisms by which climate conditions affect the development of a species can also be analysed with the CLIMEX software tool used in present study. CLIMEX is a worldwide renowned software that has recently been applied in various scientific studies considering the potential distribution and spread of animal or plant species (OLFERT, WEISS, 2006; ZALUCKI, FURLONG, 2005; RAFOSS, SAETHRE, 2003; KRITICOS, *et al.*, 2003; LOCKETT, PALMER, 2003; BELL, WILLOUGHBY, 2003; SUTHERST, 2000a; and SUTHERST, 2000b, among many others).

The main focus of present study was especially the test of models reliability in current climate of wide European domain which was carried out by

- i) the usage of already tested models for *L. decemlineata*, *C. pomonella*, and *O. nubilalis*, and their application newly in the extended European domain, models re-validation and more specification both in current climate conditions;
- ii) preparation of identical models for more pests (*L. botrana*, *O. melanopus*, *R. padi*, and *S. avenae*) in current climate and their detail validation.

MATERIALS AND METHODS

CLIMEX (CLIMatic indeEX) is a simplified computer model that infers the response of a species or biological entity to climate by using its geographical distribution, its seasonal growth pattern and its mortality in different locations (BEDDOW *et al.*, 2010). The CLIMEX program is a climate-driven modelling program that is designed to provide insight into the climatic requirements of a species, as expressed by their geographical distribution, seasonal phenology and relative abundance. The CLIMEX program assumes that it is possible to define climates that are favourable for the generation of particular weather patterns, which directly affect populations on a short time-scale (SUTHERST, 2000a). The program derives weekly and annual indices that describe the responses of a given species to changes in temperature, moisture and (in the case of plants) light (SUTHERST, 2003). These properties make CLIMEX an appropriate tool for planning questions about risk assessment issues in integrated pest management and quarantine, biological control or climatic variability and long-term climate change (SUTHERST, 2000b).

Knowing the climatological requirements of a given species allows us to assess the suitability of an area for population growth and to determine the stress induced by unsuitable climate conditions. These factors are expressed by the ecoclimatic index (EI), which describes the overall suitability of climate conditions for the establishment and long-term presence of a pest population at a given location.

$$EI = GI_A \times SI \times SX,$$

here, GI_A is the annual growth index describing population growth under favourable conditions, SI is the annual stress index describing survival during unfavourable periods, and SX is a measure of stress interactions. Stress indices were not involved in this study because the authors consider that the setup of the optimal and border developmental thresholds well expresses the climatic limits affecting the pests' occurrence. This approach was justified as accurate in the process of model validation. The calculation of the GI_A and stress indices is based on the ranges of the threshold parameters for species development and is adjusted by the user. Adjusted parameters

used in the model are in the Tab. I. The temperature parameters include the lower and upper thresholds and the optimal range of air temperature for development. Similar parameters are also used for soil moisture. In addition to the temperature and moisture limitations, CLIMEX also accounts for the process of diapause, which is driven by temperature (initiation and termination temperature) and day-length thresholds. The number of pest generations is calculated based on i) number of degree-days above the lower temperature threshold for each generation and ii) diapause development days which mean the minimum number of days required for diapause development to be completed. Generally, EI ranges from 0–100, where EI = 0 indicates climatic conditions that are unfavourable for long-term species occurrence and EI > 30 represents very suitable climatic conditions for species occurrence (SUTHERST, MYAWALD, 1985). HODDLE (2003) considers locations with EI > 25 as very favourable for species occurrence, locations with 10 < EI < 25 as favourable and locations with EI < 10 as limiting for species survival and occurrence. The CLIMEX model uses input data on a monthly scale (minimum and maximum temperatures, relative humidity at 9 a.m. and 3 p.m., and precipitation).

Validation of the modelled establishment of a particular pest was used with developmental thresholds taken from the literature (Tab. I). Visual validation of model is suggested by the model creators (SUTHERST, MAYWALD, 2005). It is the iterative geographic fitting procedure and has been used by several authors (e.g. PAUL *et al.*, 2005). The modelled pest presence was verified by comparing the observed pest occurrence with the number of generations in a given modelled area. Model parameters were then altered to truly describe the pest presence. The model was firstly tested for *L. decemlineata*, *C. pomonella*, and *O. nubilalis* in the central European domain using the 1961–1990

reference period (see SVOBODOVÁ *et al.*, 2010; KOČMÁNKOVÁ *et al.*, 2011).

Consecutive model validation within this presented study have afforded the more precise developmental thresholds for *L. decemlineata*, *C. pomonella*, and *O. nubilalis* especially moisture thresholds were newly assessed in the process of validation test in extensive European area. The remaining pests' models along with their validation are described in this study. Models verification has took into account the harmfulness and the number of generations throughout the Europe (Figs. 1–7). Validation was assessed within the European domain with the CRU TS 1.2 data (NEW *et al.*, 2000; MITCHELL *et al.*, 2003) for the current climate (1961–2000).

RESULTS AND DISCUSSION

CYDIA POMONELLA

Especially temperature is considered to be the determining factor of the life-cycle length and consequently of a number of completed generations. Codling moth (*Cydia pomonella*, Linnaeus, 1758) is the oldest known and the most widely distributed pest of deciduous pome fruit (FERRO, HARWOOD, 1973). Native home of the codling moth is considered to be south-eastern Europe from which it spread to various parts of the world and now occurs in the temperate regions of all major continents. It has demonstrated an ability to colonize apple and pear trees wherever the climate is suitable for their commercial production. It is evident that present distribution of codling moth is related to climatic factors as well as to food conditions (WEARING, *et al.*, 2001).

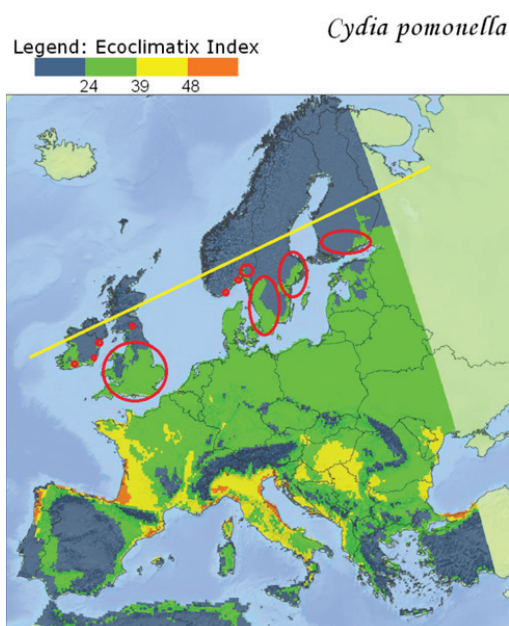
The codling moth now occurs in the temperate regions of all major continents. It is widespread throughout Europe north to southern Scandinavia and eastward to Siberia, to north India, and to

I: Parameters of the CLIMEX model for the development of *Leptinotarsa decemlineata* (Colorado potato beetle, CPB), *Ostrinia nubilalis* (European corn borer, ECB), *Cydia pomonella* (Codling moth, CM), *Lobesia botrana* (European grape wine moth, EGM), *Oulema melanopus* (Cereal leaf beetle, CLB), *Ropalosiphum padi* (Bird-cherry aphid, BCA), and *Sitobion avenae* (Grain aphid, GA) used in the study

Development thresholds	CPB	ECB	CM	EGM	CLB	BCA	GA
Lower temperature threshold (°C)	10.00	10.00	9.00	10.00	9.00	3.38	3.90
Optimum range of temperatures (°C)	18.00	15.00	15.00	16.00	10.00	21.00	20.00
	28.00	28.00	27.00	29.00	20.00	25.00	23.00
Higher temperature threshold (°C)	35.00	38.00	34.00	32.00	32.00	30.00	30.00
Lower soil moisture threshold	0.15	0.06	0.10	0.01	0.02	0.20	0.20
Optimum range of soil moisture	0.35	0.15	0.17	0.10	0.10	0.30	0.50
	0.80	1.20	1.50	1.30	1.20	1.20	1.20
Higher soil moisture threshold	1.50	2.00	2.50	1.40	1.50	1.30	1.40
Diapause induction daylength (h)	13.50	14.50	14.00	13.00	14.00	-	-
Diapause induction temperature (°C)	13.00	12.00	10.00	26.00	11.00	-	-
Diapause termination temperature (°C)	8.00	8.00	6.00	10.00	6.00	-	-
Diapause development days	-	-	90	-	-	-	-
Degree-days per generation	400.0	726.0	580.0	430.0	490.0	149.2	150.8

Xinjiang and Gansu in China. It is widely established in Africa and occurs on a number of islands, such as Madeira, Canary Islands, and Mauritius. The codling moth has demonstrated an ability to colonize apple and pear trees wherever the climate is suitable for their commercial production.

In our study as a validation material were used records about generation number of the moth across the European area. Codling moth develops one generation in the coldest regions, four or five generations in the hottest regions, generally three generations are present in Spain (GONZALES, 2007), two generations in Romania (NEAMTU *et al.*, 2008), three generations in Italy (REGGIANY *et al.*, 2006). In the Czech Republic *C. pomonella* completes maximally two generations per season (SPA, 2007). There are usually two pest generations during the year in Slovak Republic (BAYER, 2007). Number of generations assessed by the simulations is in the agreement with records mentioned above (Fig. 1). In addition simulated northern boundary of the pest occurrence area corresponds with detail geographical localization approachable in the Global biodiversity information facility website (<http://data.gbif.org/occurrences/>).



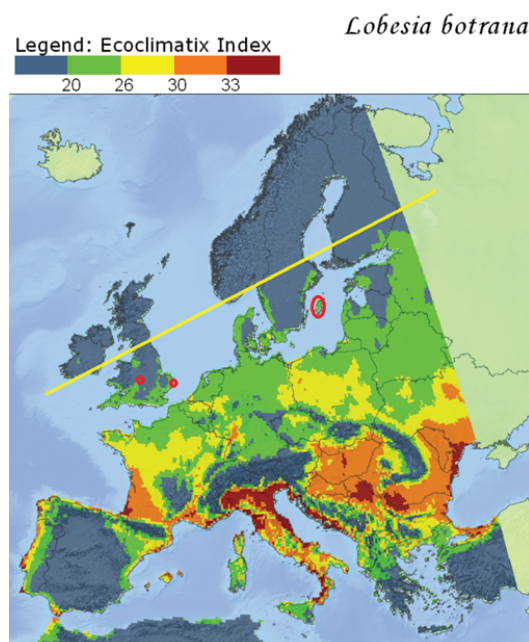
1: CLIMEX simulation: visualisation of Ecoclimatic index representing climate conditions favourable for the establishment of one (green), two (yellow) and three (orange) generations of *C. pomonella*. Red circles mark observed occurrences of the pest available in database of Global Biodiversity Information Facility. Yellow line constitutes potential northern range as was estimated based on the CLIMEX results.

LOBESIA BOTRANA

European grapevine moth *L. botrana* is a significant pest of berries and berry-like fruits in Europe and the Mediterranean. *L. botrana* is native to southern

Italy and was first described by biologists Denis and Schifferrmüller in 1775 in Vienna, from samples collected in Italy, and was classified as a pest in Austria in 1800 (VARELA *et al.*, 2010). This moth is now distributed in vineyards throughout Europe (CABI Distribution Maps of Plant Pests, www.cabi.org). The currently reported global distribution of *L. botrana* suggests that the pest may be most closely associated with biomes classified as montane scrub, Mediterranean scrub, and temperate broadleaf and mixed forests (VENETTE *et al.*, 2003).

The number of generations is determined by several factors including photoperiod, temperature, humidity, latitude, food quality, and the effects of predators and diseases (DESEO *et al.*, 1981). In response to differences in climate, the number of generations completed by *L. botrana* differs geographically. In general, more generations are completed in southern latitudes than in northern latitudes. Two generations occur in colder areas of Europe whereas this species typically has three generations in southern Europe. Up to four generations can be completed in warmer regions such as Greece (MOSCHOS *et al.*, 1998). Two or three generations are present in Germany (Lous *et al.*, 2002). Simulations using CLIMEX have estimated the climate conditions favourableness for completion of number of generations corresponding with numbers in relevant European countries mentioned above (Fig. 2). However, it seems to be some inaccuracies in results of the



2: CLIMEX simulation: visualisation of Ecoclimatic index representing climate conditions favourable for the establishment of one (green), two (yellow), three (orange), and four (red) generations of *L. botrana*. Red circles mark observed occurrences of the pest available in database of Fauna Europea or Suffolk Moth Group. Yellow line constitutes potential northern range as was estimated based on the CLIMEX results.

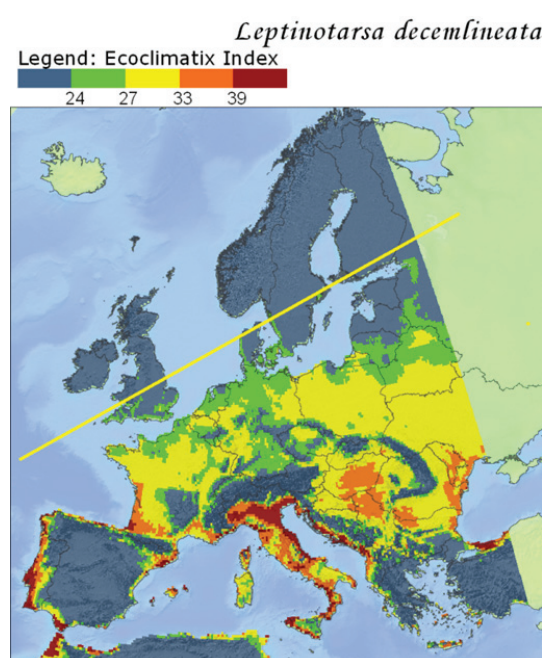
models; even though there is a disagreement in the *L. botrana* presence in Poland according to CABI and Fauna Europea (www.faunaeur.org), the second in line indicates the moth as surviving in this area. Also CLIMEX indicated climate conditions as suitable for its survival in this area. The potentially presence of this pest in Poland is supported and allowed by the fact that Poland manages 250–300 ha of vineyards (LISEK, 2008).

The next disagreement refers the Scandinavia; both CABI and Fauna Europea indicate *L. botrana* absence in Norway, Denmark, and Finland; CLIMEX marks Denmark and southern border of Sweden and Finland as northern limit for *L. botrana* occurrence. CLIMEX besides correctly indicates the climate suitability in Gotland (moth presence recorded by Fauna Europea). In Denmark and Finland is *L. botrana* present most likely indoor interceptions (Canadian Food Inspection Agency, www.inspection.gc.ca). The next controversial region is United Kingdom where *L. botrana* is a rare immigrant in Suffolk (web site of the Suffolk Moth Group, www.suffolkmoths.org.uk), CLIMEX had assessed the climate of this region in the agreement with this claim.

LEPTINOTARSA DECEMLINEATA

The Colorado Potato Beetle, *L. decemlineata* (Say), one of the most destructive pests of potato. The beetle is present throughout Europe except for Britain, Ireland and Scandinavia, having its northern range limit in Russia (60°N) (EPPO, 2006). The development of this species is closely related to climate conditions, especially to temperature patterns. The number of Colorado beetle generations is largely a function of temperature, varying between about four in the hottest areas to one full and one partial generation near the colder extremes. There are some cold areas with only one partial generation (EPPO). Low temperatures are the main hindrance for their survival and spread, and determine the borders of the beetles distribution (HIIESAAR *et al.*, 2006).

CLIMEX model for *L. decemlineata* was validated in previous studies and occurrence with number of generations was corresponding with real state in the whole domain of central Europe (KOCMÁNKOVÁ *et al.*, 2011). In wider spatial approach there is crucial the northern limit of *L. decemlineata* where the main role constitutes the climate favourableness of UK and Sweden. In these states *L. decemlineata* is quarantine i.e. regulated pest (DEFRA, www.defra.gov.uk) which means that climate conditions would allow the establishment of the pest but pest management till this time successfully had avoid the long-term survival. CLIMEX correctly indicates climate of south and south-eastern part of England as potentially suitable for the establishment of the pest. Similarly the southern border of Sweden constitutes the potential climatic niche for *L. decemlineata* presence (Fig. 3).



3: CLIMEX simulation: visualisation of Ecoclimatic index representing climate conditions favourable for the establishment of one (green), two (yellow), three (orange), and four (red) generations of *L. decemlineata*. Yellow line constitutes potential northern range as was estimated based on the CLIMEX results.

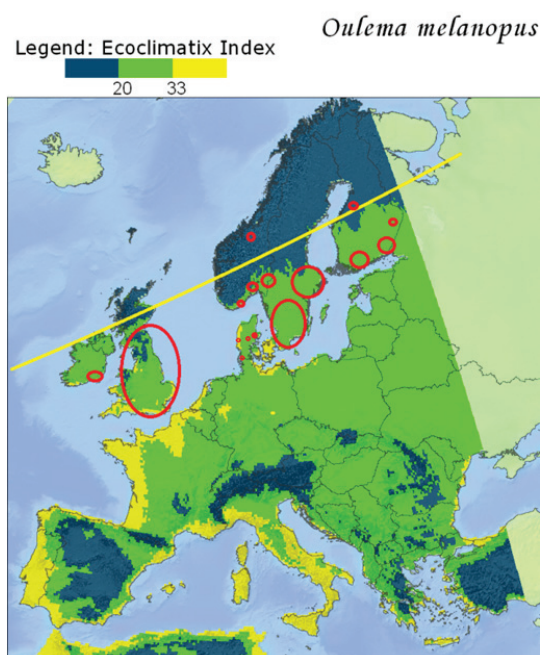
OULEMA MELANOPUS

Cereal leaf beetle, *O. melanopus*, is an invasive pest of small grain cereal crops, particularly of wheat, oats, and barley (CAB INTERNATIONAL, 2002). This species is now present throughout the whole Europe with the inclusion of Scandinavia. *O. melanopus* typically have one generation per year, but occasionally two years are necessary to complete development of a single generation in more northern climates (NCSU, 2003).

The assessment of the climate suitability for the establishment of *O. melanopus* was, due to the obligate univoltinism of the pest, evaluated in three levels e.g. no suitable, suitable and very suitable climate. In the validation process is fundamental, as in other cases of modelled pests, the pest presence in northern areas especially in Norway, Sweden, Finland, and Denmark where the species is currently present and output of the model declares the same. In addition *O. melanopus* is widely spread in United Kingdom and in Ireland which was also simulated by the model. As well were fulfilled the moisture requirements of the pest in southern countries like Greece and Italy (Fig. 4).

OSTRINIA NUBILALIS

European corn borer *O. nubilalis* is the most important pest of grain maize native and widely spread in Europe. Under the current climate conditions, *O. nubilalis* has one to three generations per year, depending on the latitude and temperature conditions. In northern areas has one or one partially



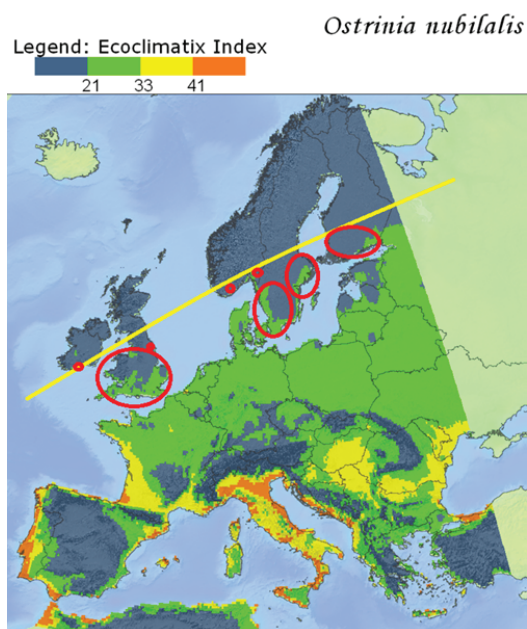
4: CLIMEX simulation: visualisation of Ecoclimatix index representing suitable (yellow) and very suitable (green) climate conditions for the establishment of *O. melanopus*. Red circles mark observed occurrences of the pest available in database of Global Biodiversity Information Facility (<http://data.gbif.org/>). Yellow line constitutes potential northern range as was estimated based on the CLIMEX results.

generation, in central Europe i.g. in Hungary has one generation in north-western and two in southern part of country (KESZTHELYI, LENGYEL, 2002). Partial second generation has been proven under field conditions in Slovakia and Poland (Cagáň *et al.*, 2000; Tancik, Cagáň, 2004). In warmer areas the pest can complete two or three generations (south-west of France, Italy). Validation of the model was carried out coupled with the model of *L. decemlineata* in the domain of central Europe (KOCMÁNKOVÁ *et al.*, 2011), in this domain there was fulfilled the number of generations according to observation records. In the whole European scale the model, in the agreement with the real occurrence, simulated the higher number of generations in Italy and generally in France. This species is long-term established also in northern states like Norway, Sweden, Finland, Denmark, United Kingdom, and Ireland (Fig. 5). All these states are according to CLIMEX simulations occupied by one generation of *O. nubilalis*.

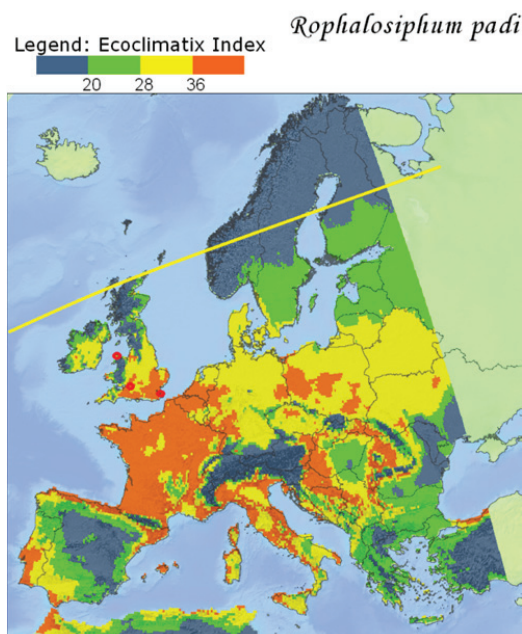
RHOPALOSIPHUM PADI, SITOBION AVENAE

Both aphid species as pests of cereals are an important vectors of plant viruses that may cause considerable injury, the most important among them is BYDV (Barley yellow dwarf virus).

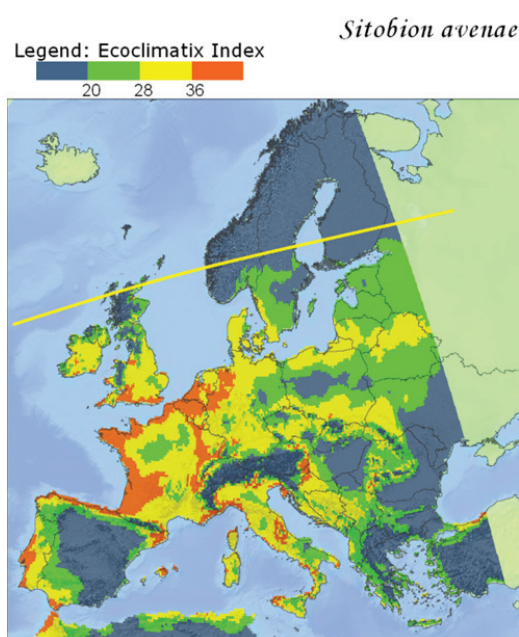
Distribution of cereal aphids is generally affected by climatic conditions and some biotic factors such



5: CLIMEX simulation: visualisation of Ecoclimatix index representing climate conditions favourable for the establishment of one (green), two (yellow), and three (orange) generations of *O. nubilalis*. Red circles mark observed occurrences of the pest available in database of Global Biodiversity Information Facility (<http://data.gbif.org/>). Yellow line constitutes potential northern range as was estimated based on the CLIMEX results.



6: CLIMEX simulation: visualisation of Ecoclimatix index representing climate conditions favourable for the establishment of eight (green), twelve (yellow), and sixteen (orange) generations of *R. padi*. Red circles mark observed occurrences of the pest available in database of Global Biodiversity Information Facility (<http://data.gbif.org/>). Yellow line constitutes potential northern range as estimated based on the CLIMEX results.



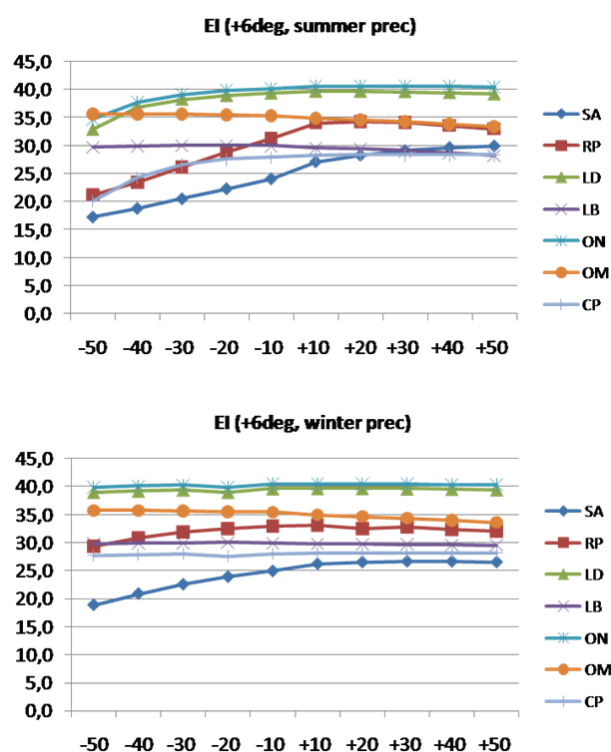
7: CLIMEX simulation: visualisation of Ecoclimatic index representing climate conditions favourable for the establishment of eight (green), twelve (yellow), and sixteen (orange) generations of *S. avenae*. Yellow line constitutes potential northern range as was estimated based on the CLIMEX results.

as the quality of host plants, dispersal efficacy and natural enemies (ELLIOT, KIECKHEFER, 2000).

Bird cherry-oat aphid *R. padi* is one of the most damaging aphid worldwide (LEATHER *et al.*, 1989). The English grain aphid, *S. avenae*, is an important pest especially in temperate climates on the northern and southern hemisphere (WANGAI *et al.*, 2000).

Geographical distribution of both species is almost all-European including the Scandinavia, UK, Ireland and also southern location as Italy or Sicily. These data are obtained from CABI and Fauna Europea database mentioned above. These databases, however, don't determine more detailed specification of the pests' occurrence so for the verification of the model we must to manage with the common determining in state scale. CLIMEX model offers specifying of infested area such as Norway where CLIMEX estimated climate conditions suitable for both species in south-eastern coast only or southern coast of Finland suitable for population of *S. avenae* (Figs. 6, 7). The verification of the generation number is rather problematic due to the complicated and variable reproduction cycle of aphids. Based on the course of weather and season aphids diversify the sexual and parthenogenetic reproduction so the collection of the summary of the generation number is rather problematic. But there are some records in England where for instance *S. avenae* can develop eighteen generations, this threshold was realised in CLIMEX too.

Sensitivity analysis demonstrated that temperature is the obvious factor determining the



8: Dependency of EI on combination of temperature increase (+6 °C) and change of precipitation amount (%) in summer season (above) and winter season (below).

species development. Value of EI for all species was increasing linearly in the parallel with increasing temperature up to the level of +4 °C. For temperature increase higher than 4 °C the analysis estimated the EI slowly decreased for *C. pomonella* and *L. botrana*, however, these decreased EIs were still higher than starting point representing present climate. Test of species development related to precipitation estimated the sensitivity especially of aphids *S. avenae* and *R. padi* to decreasing precipitation in summer season (AMJJAS) (Fig. 8 above).

Significant was the detection of aphids reaction to winter precipitation decrease (Fig. 8). 50% precipitation decrease during the winter period (ONDJFM) which caused the EI decreased almost about 12 for both species. This EI decline is given by i) aphids requirements to high humidity, ii) longer season of aphids activity. Aphids activity could still continue in first two months in winter

season (October, November) and their specific lifecycle allows nymphs and parthenogenetic females to overwinter and be active in early spring. Figure 8 depicts the change of EI in relation to the combination of temperature increase and precipitation change in winter and summer season for all species.

CONCLUSION

Parameterization of the factors causing distribution patterns of study species was successful and modelled potential distributions of species correspond well to known core distribution areas for all of these species. Sensitivity analyses using changing meteorological items revealed especially the aphids dependency on decreasing precipitation both in summer and winter season.

SUMMARY

Present study was focused on the validation of seven pests occurrence models in wide European domain. Used climate matching tool (CLIMEX) exploited the known dependency of pests development and climate conditions which was expressed by climatic parameters driving the pests development in the simulation. Potential occurrences of all species according to the model were compared with their real occurrences and number of generations across the Europe. Based on this comparison the climatic parameters determining the pests development were iteratively altered to truly describe the current pests occurrence. Examined sensitivity analysis affirmed the expected species dependency on temperature and especially proved the aphids sensitivity on precipitation decline. Results of this study are expected to be initial for further study of the pests occurrence according to climate change scenarios in European domain.

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Address

Ing. Eva Svobodová, Ph.D., doc. Mgr. Ing. Miroslav Trnka, Ph.D., RNDr. Martin Dubrovský, Ph.D., Ing. Daniela Semerádová, Ph.D., prof. Ing. Zdeněk Žalud, Ph.D., Department of Agrosystems and Bioclimatology, Mendel University in Brno, Zemědělská 1, 613 00 Brno, Czech Republic, prof. Josef Eitzinger, Institute of Meteorology, University of Natural Resources and Life Sciences (BOKU), Vienna, Austria, Ing. Petr Štěpánek, Ph.D., CzechGlobe-Global Change Research Centre, v.v.i., AS CR, Bělidla 4a, 603 00 Brno, Czech Republic, e-mail: e_svobodova@yahoo.com