

Predicting climate change induced vulnerability of African agricultural systems to major insect pests through advanced insect phenology modeling, and decision aid development for adaptation planning

Project Proposal

A proposal for: Das Bundesministerium für Wirtschaftliche Zusammenarbeit und Entwicklung (BMZ)

Project Funding for International Agricultural Research Centers

Submitted by: International Potato Center (CIP), Lima, Peru



In collaboration with

The International Institute for Tropical Agriculture (IITA), Ibadan, Nigeria

The International Center for Insect Physiology and Ecology (ICIPE), Kenya, Nairobi

The University of Hohenheim, Germany



and

The System wide Program on Integrated Pest Management (SP-IPM)



March 31, 2009

1. Project summary

1.1 The IARC applicant

The International Potato Center (CIP)

1.2 Project title

Predicting climate change induced vulnerability of African agricultural systems to major insect¹ pests through advanced insect phenology modeling, and decision aid development for adaptation planning

1.3 Budget requested from GTZ/BMZ (in Euro) and project duration

The overall budget requested amounts to Euro 1.2 million for a duration of three years.

1.4 Project description

Climate change will precariously affect agricultural production and the livelihood of farmers in Africa by unpredictably changing the abundance of insect pests along with their existing and potential natural enemies. The project seeks - through innovative phenology modeling and risk mapping - to understand the effects of rising air temperatures caused by climate change on the future distribution and severity of major insect pests on important food crops in Africa. This will be achieved through the development of generic analytical tools (software for decision making) that require and foster collaboration through joint model development and application of modeling results for adaptation planning addressing the different stakeholders' and target pests. As a result, the scientists of national research institutions in Africa will be trained in applying simulation methodologies to assess the vulnerability of agricultural systems to major pests - due to climate change - and to identify adaptation strategies to cope with future pest problems. The project builds on CIP's experience in insect simulation modeling and risk mapping, as well as, on the provision of Insect Life Cycle Modeling (ILCYM) software. This software will be further improved and adapted to cover a wide range of insect pests, and to meet the needs of the different stakeholders. The results will fill the current knowledge gap about climate change effects on economically important insect herbivores, especially in the tropics. The project is a collaborative effort of three International Agricultural Centers (CIP, IITA, and *icipe*), the University of Hohenheim, Germany, and their partners at NARI in Africa. The project goal, purpose/outcomes and outputs are as follows:

Goal:

African agriculture (farmers, national agricultural research institutions, policy makers, etc.) copes with the risk of exacerbating and expanding insect pests due to climate change; and, adaptation strategies minimize major pest-related crop losses.

Purpose/outcomes:

- Vulnerability of crops to pests induced by climate change determined through phenology modeling, and a database on temperature-driven phenology models developed and computer-aided tools provided for pest risk mapping and adaptation planning.
- Scientists and IPM practitioners use the project tools for: country-specific pest risk assessments, adaptation planning, improving their pest management strategies, and for providing information to policy makers to improve national pest management and quarantine programs.

Outputs:

Output 1: Present distribution (mapping) of selected target pests and associated natural enemies elaborated according to climatic factors and pest severity with parasitoid efficacy concomitantly determined.

¹ In the whole proposal we use the term insect instead of arthropod although one mite (*Acari*) species is considered in the research.

Output 2: Phenology models for highly economic and invasive agricultural pests of global or regional economic importance developed and validated, and their potential to increase infestation and to expand present distribution due to climate change determined.

Output 3: Phenology models for specific beneficial arthropod species that are considered strong antagonist of the target pests developed, validated, and linked with the related pest phenology models (two-species-interaction models).

Output 4: NARS scientists in pest risks assessments using ILCYM software trained and adaptive pest management strategies to cope with new emerging pest problems identified.

Output 5: A developmental database to support phenology models for insect pests and their antagonists established and published and the freely available ILCYM software further improved.

Countries involved:

Benin, Cameroon, Kenya, Tanzania, Uganda.

1.5 Project justification

Societies in Africa are highly dependant on agriculture, an activity traditionally vulnerable to existing climatic conditions. Any increase in temperature, caused by climate change, coupled with a decline in rainfall will have drastic consequences on the production of crops. This will exacerbate existing vulnerabilities of the poorest people who depend on agriculture. Insect pests represent major constraints to agricultural production in Africa. Warmer temperatures will have substantial effects on these pests resulting very likely in greater frequency and severity of outbreaks, changes in abundance and distribution. Therefore, if adequate pest management strategies are not developed and made available to farmers it could, ultimately, lead to greater crop and quality losses. Pesticides are out of reach to poor subsistence farmers in Africa, who depend on natural control of pests provided by a range of natural enemies. Some of these natural enemies have been successfully naturalized in classical biocontrol programs for a wide range of pests and crops. Future pest management will very likely depend on the resilience of agricultural ecosystems and how natural enemies will control pests under changing environmental temperature. The collaboration of IARCs and NARIs scientists will make it possible to assess the consequences of climate change for a wide range of pests (of different insect orders and families, and one mite species) of important agricultural crops in Africa. In addition, the impact of increased temperature will also be studied on selected pests' natural enemies, and this study will provide clues for the future resilience of agricultural systems to cope with pest problems.

1.6 Expected uses and users of research results

Direct beneficiaries are scientists from NARI and IARC (and the scientific community at large), as well as, IPM practitioners. These beneficiaries will apply the project results and modeling tools in their research for developing country specific IPM strategies, and for providing appropriate pest management recommendations to policy makers. Final beneficiaries are farmers who profit from more effective and timely-provided pest control measures, or even from prevention of insect pest outbreaks due to appropriate pest management and quarantine interventions.

1.7 Research methodology and procedure

Innovative insect phenology modeling and risk mapping in a Geographic Information Systems (GIS) environment will be used to assess future impacts of climate change on agricultural pests. Process-based phenology models that use a number of functions describing temperature-driven processes, like development, mortality, reproduction, etc. in insect species, will be developed. A cohort up-dating algorithm and rate summation approach is used for simulating multidimensional age and stage structured populations. Input data are minimum and maximum daily temperature (real or interpolated data). Simulation results, like life-table parameters (i.e. net reproduction rate, mean generation time, intrinsic and finite rate of increase, and doubling time), can be plotted over time; for analysis of the pests' risk in space three generic risk indices (Index for Establishment,

Generation Number and Activity Index) can be visualized in GIS maps. The functions and parameters for a given phenology model will be determined based on existing literature data and insect life-table studies carried out over a range of temperatures. The different project partners (IARC, NARI) will work on different pest species and related parasitoids. Models will be produced with a current version of Insect Life Cycle Modeling (ILCYM) software developed by CIP (Version 2.0, available at CIP web-site: <http://www.cipotato.org>). ILCYM software provides a “model builder” for facilitating determination of the equations used and compilation of the final model, and analysis tools for validating established models by comparing simulation results with field-derived life-table data. It should be noted that although the “model builder” might not currently provide solutions for each insect species under study, it will be adjusted to a wide range of pests as a project result. To assess pest-natural enemy interactions two-species-interaction models will be developed. GIS tools implemented into the ILCYM software will be used to produce risk maps. Regional and national scale simulation will be based on WorldClim data or other data sets, including real or historical data, which provide higher accuracy and allow further downscaling. To forecast the pests’ risk under climate change scenario maps will be generated using temperature forecasts from an atmospheric general circulation model (GCM), described by Govindasamy et al. (2003), which is currently implemented in ILCYM software; however, the GCM can be exchanged if required. The process-based modeling approach allows for integration of further biotic or abiotic factors ruling on pest populations (e.g., precipitation, management practices and their effects on specific life stages of the pest, etc.). These factors are pest specific and require additional experiments for model parameterization and their integration into the overall model. ILCYM software will be further improved during the course of the project to better meet the requirements of the different stakeholders (research, extension, decision support for IPM practices).

1.8 Conclusions of completed activities

Insect phenology modeling and risk mapping tools can be used for predicting, with a high probability, future pest risks under climate change scenarios. Modeling tools have been applied for the potato tuber moth in a world-wide and regional scale (Annex 3, Fig. 1 to 3). ILCYM software allows national programs to undertake modeling and adaptation to climate change studies without the capacity need to develop new mathematical models. Development of decision-making tools, for globally important pest species, calls for broad collaboration between countries and institutions, and information sharing. Our approach is to develop generic analytical tools, which foster collaboration through joint model development, validation and application. Models should be managed in a collective database and up-dated or modified when additional research results are obtained. Therefore, the project will initiate networking and conduct workshops on ILCYM; and disseminate the information to the wider community using the www with the goal to achieve a broader ILCYM modeling network on economically important arthropod pests.

1.9 Stakeholders

1) Poor farm households in Africa where cereals, root and tuber crops and fruits are important components of farming systems; 2) National research and governmental organizations in Africa; 3) CGIAR and other international research organizations and NGOs.

1.10 Project coordinator

Dr. J. Kroschel (Head Agroecology/IPM), j.kroschel@cgiar.org; in collaboration with: **Dr. M. Sporleder** (Entomologist), m.sporleder@cgiar.org, **R. Simon** (Head Research Informatics Unit/GIS lab), r.simon@cgiar.org

1.11 Collaborating institutions and staff, including NARS

Dr. R. Hanna (Entomologist/Biocontrol Specialist), International Institute for Tropical Agriculture (IITA), r.hanna@cgiar.org; **Dr G. Goergen** (Biodiversity Specialist), IITA, g.goergen@cgiar.org; **Dr. A. Chabi-Olaye and Dr. B. Le Ru** (Entomologists), International Center for Insect Physiology

and Ecology (*icipe*), achabi@icipe.org, bleru@icipe.org; **Dr. I. Hoeschle-Zeledon** (coordinator SP-IPM) (IITA), i.zeledon@cqiar.org

NARS: Kenya: Kenya Agricultural Research Institute (KARI) and **Prof. E. Kairu**, Kenyatta University; Uganda: Namulonge Agricultural Research Station and Makerere University, **Dr. R. Molo**, richardmolo@yahoo.com; Tanzania: Biocontrol Programme, PO Box 30031, Kibaha, Beatrice Pallangyo. beatricepallangyo@yahoo.com; **Pr. A. Agbaka**, University of Abomey-Calavi, Cotonou, Benin; **Pr. A. Fomena**, University of Yaoundé I, Yaoundé, Cameroon.

1.12 Cooperation with German research institution

Prof. Dr. C. P. W. Zebitz, Applied Entomology, University of Hohenheim (UoH) (360), Germany. Email: zebitz@uni-hohenheim.de. Area of cooperation: Expertise in Entomology, insect life-tables and modeling; PhD and Master student supervision.

1.13 Major research domains (only key words) and positioning of the project within German thematic funding priorities

Insect pest management, phenology modeling, insect pest risk analysis and mapping, biological control. Seventh Priority: Adaptation of African Agriculture to Climate Change.

1.14 Positioning of the project on the research-development continuum

The project will cover the research-development continuum from basic entomological research (insect life-tables of pests and associated natural enemies related to temperature; pest infestations and parasitism rates in different environments), developing process-based insect phenology models and risk assessments models supported by GIS, the development of user-friendly modeling software, to the training of national partners using this software for climate change pest risk assessments for adaptation planning.

1.5 Budget summary

Expenditure (Euro)	GRAND TOTAL FROM BMZ				Total
	Year 1-3				
	CIP	<i>icipe</i>	IITA	UoH	
	Total	Total	Total	Total	
Personnel	374,114	41,400	86,400	0	501,914
Supplies & operational	63,600	39,600	33,600	0	136,800
Equipment	21,000	2,500	2,500	2500	28,500
Training/Workshop*	110,000	51,000	6,000	82,500	249,500
International Travel	62,900	7,400	8,900	7,500	86,700
Publications	34,650	3,000	3,000	0	40,650
Other expenses	5,400	1,800	1,800	1,800	10,800
Total	671,664	146,700	142,200	94,300	
Indirect costs (%)	87,316	29,340	28,440		
Grand total	758,980	176,040	170,640	94,300	1,199,960

*The total budget included for training of NARI scientists amounts to EURO 167,000. This considers training of Bsc/PhD students (PhD: EURO 45.000; MSc.: EURO 42.000 BSc), specific training (EURO 50.000) and research activities on life-tables (EURO 30.000).

2. Background

Climate change and impact on African agriculture

Today, it is widely accepted that the Earth's climate has become increasingly warmer, most likely due to increasing greenhouse gas emissions. Climate change - a phenomenon synonymous with global warming and the greenhouse effect - is projected to continue. Major effects of climate change will be: i) a rise of the mean temperature between 1.5 to 5.8 °C by the end of the next century; ii) an increase in the frequency of droughts; iii) an increase of sea levels and the frequency of floods and heavy rains; and iv) an alteration of wind directions (IPCC 2001). Recent predictions forecast, with a high probability (>90%) higher growing season temperatures in the tropics and subtropics that will exceed the most extreme seasonal temperatures recorded in the last century (Battisti and Naylor 2009). The global environmental change is amongst the greatest long-term threats to humans today. Climate change is expected to exacerbate the already serious challenges to food security and economic development, especially on the African continent where people are already struggling to meet challenges posed by existing climatic variability (IPCC 2007, Slingo et al. 2005). A total of 330 million people live in extreme poverty in sub-Saharan Africa with 70% of the population surviving by subsistence agriculture (Hellmuth et al. 2007). The agricultural sector is a major contributor to the current economy of most African countries ranging from 10% to 70% of the gross domestic product (GDP) with the slowest record of productivity increase in the world. Climate change is likely to reduce agriculture's share of GDP (Mendelsohn et al. 2000), e.g., crop productivity will be greatly affected in Africa and overall yields such as for maize may fall by 10 to 20% by the year 2055 because of warming and drying (Jones and Thornton 2003, Thornton et al. 2006). Adaptation to climate change seems to be especially relevant for Africa (Thomas and Twyman 2005) and climate derived information is most likely to improve development outcomes when it is integrated into a framework for decision making to specific risks (Hellmuth et al. 2007).

Effect of climate change on arthropod pests and pest-natural enemy interactions

On average, 30 to 50% of the yield losses in agricultural crops are caused by pests despite the application of pesticide to control them (Oerke et al. 1994). Insects are the most diverse class of organisms on Earth; they have either direct or indirect detrimental and beneficial effects on humans and natural ecosystems. Climate, especially temperature, has a strong and direct influence on insect development, reproduction and survival (Andrewartha and Birch 1955, Uvarov 1931) and is considered under climate change the dominant abiotic factor directly affecting herbivorous insects (Bale et al. 2002). Since insect population growth potentials are mainly temperature driven, a rise in temperature may either increase or decrease insect development rates and related crop damages depending on the insect species optimum temperature range. Considerable attention has already been given to the impacts of climate change on insects in temperate regions (Ward and Masters 2007, Battisti et al. 2006, Harrington et al. 2001, Volney and Fleming 2000, Cammell and Knight 1992, Porter et al. 1991). Here, milder winters will increase the survival rate of pests and will allow a faster population recovery and build-up in spring (Bale et al. 2002). The growing season is expected to become extended and could benefit multivoltine species to produce a larger number of generations and also increase the risk for invasive pest species (Ward and Masters 2007).

Depending on the complexity and species richness, agroecosystems can have a good potential to provide a high level of natural biological control, and hence ecosystem complexity can increase ecosystem resilience to pest outbreaks. However, little is known on how climate change may affect multitrophic levels or competitive interactions. Recent studies indicate that climate change can dissociate predator-prey relationships, because of a higher sensitivity of higher trophic levels to climatic variability or of different temperature optima compared with pests (Voigt et al. 2003). In

this respect, divergences in the thermal preferences of the pest and its natural enemy will lead to a disruption of the temporal or geographical synchronization, increasing the risk of host outbreaks (Hance et al. 2007). Additional negative effects might be a decrease in the fitness of natural enemies due to changes in herbivore quality and size induced by temperature (Thomson et al. 2009). As a result, these authors suggested a careful analysis on how host-natural enemy systems react to changes in temperature to predict and manage the consequences of global change at the ecosystem level. This might negatively affect successful classical biocontrol programs, in which an increase in temperature could give a comparative advantage to the pest population growth compared with its biocontrol agent. We will test the hypotheses that climate change will directly and indirectly affect insect pest abundance and severity in agricultural and horticultural crops in Africa using ILCYM software and that this will most likely lead to greater yield and quality losses caused by arthropod pests.

How the problems of the beneficiaries have contributed to this research proposal

Compared with temperate regions, tropical countries are known to be more prone to pest problems and outbreaks because of the year-round favorable climatic conditions for pest population growth and food (host) availability. However, studies on how climate change will aggravate the pest situation in Africa are lacking. This, in spite of the fact, that a large number of insect pests are one of the major economical constraints to agricultural production. The majority of these are introduced pests such as cassava mealybug (*Phenacoccus manihoti*), cassava green mite (*Mononychellus tanajoa*), spotted stemborer (*Chilo partellus*), potato tuber moth (*Phthorimaea operculella*), and many others (Abate et al. 2000), all of which could develop high populations in the absence of natural enemies. Fortunately, for nearly all of these introduced pests, classical biocontrol could provide important control (Neuenschwander 2003, Kfir 2003, Yaninek and Hanna 2003, Hanna et al. 2005). Variability of climate, such as that associated with El Niño events, has shown large impacts on crop production (Slingo et al. 2005). Lessons learnt from the El Niño phenomena can be used for predictions and a better understanding of possible climate change effects on pest abundance and severity in agricultural crops. During the last El Niño phenomena in Peru in the year 1997, mean temperatures increased by about 5 °C above the annual average. At the same time, while infestation of potato (*Solanum* sp.) by the leafminer fly *Liriomyza huidobrensis* decreased, infestations by the bud midge *Prodioplosis longifila* devastated the crop (Cisneros and Mujica 1999). In general, in all annual and perennial crops investigated (sweetpotato, cotton, maize, asparagus, citrus, apple and peach) an increase in pest abundance and infestation severity could be observed. The farmers' only adaptive strategy to cope with this unusual situation was the weekly application of high dosages of pesticides. It can be expected that climate change consequences and farmers' future needs for adaptation in Africa will be quite similar to that described above.

Analysis of relevant current research and review of literature

Models are important analytical tools for evaluation, understanding and predicting the dynamics of insect populations in ecosystems under a variety of environmental conditions and management practices, and more recently are also used in phytosanitary risk assessments (Baker 1991, Jarvis and Baker 2001a, b). There are two distinct approaches prevalent in the modeling of insect pests and the risk of establishment and expansion, which are not necessarily competing but might also be used complementarily. The first approach uses climate match functions that seek out the potential exploitation of a non-indigenous invasive species to new areas by comparing the long-term meteorological data for each of a selected location where the species is absent with the location of origin or locations where the species prevails (Sutherst and Maywald 1991, Sutherst et al. 2000). For the application of this approach computer-aided tools such as CLIMEX (Peacock and Worner 2006, Wilmot Senaratne et al. 2006) and BIOCLIM (Kohlmann et al. 1988, Steinbauer et al. 2002) have been developed and used. This approach has been used to predict insect species' demography for pest risk analysis (Suthers 1991, Zalucki and Furlong 2005,

Rafoss 2003) and possible climate change effects (Sutherst and Maywald 1990). It uses minimal data sets and simple functions to describe the species' response to temperature and other climatic factors. "Matching indices" might indicate the similarity between areas for selected climatic variables. The second approach uses a process-based climatic response model for an insect species of interest (phenology model), which is based on detailed laboratory assessments for parameter determination, that produces life-table parameters and allows the simulation of populations according to real or interpolated temperature data for a given region and time. The difference between the two approaches is in the level of abstraction, which is higher in the 'match climate' approach and in which the mathematical methods employed lead to a greater generality. Instead, process-based phenology models are either detailed or simplified mathematical models, which describe the basic physiological principals of insect species' growth this means its development, survival and reproduction.

Insects cannot internally regulate their own temperature (exothermic organisms) and their development depends on the temperature to which they are exposed to in the environment. They require a certain amount of heat to develop from one developmental stage to another in their life-cycle (Uvarov 1931, Andrewartha and Birch 1955). Degree-day models have been established describing development in different insect pests, which employ linear models using accumulation of temperature above the minimum temperature threshold (Allen 1976; see Nietschke *et al.* 2007 for available referenced insect development databases). However, due to the non-linearity of the development curve, especially when temperature deviated from the intrinsic optimal temperature of the species these models are poor predictors of insect development. This method works well for intermediate temperatures, but produces errors (significant deviations from the real development) when daily temperature fluctuates to extremes (Stinner *et al.* 1974, Worner 1992). Modern, more progressive models use non-linear models of higher biological significance (i.e. Sharpe and DeMichele (1977), Logan *et al.* (1976), etc.), and include stochastic functions for variability in development times within a population among individuals (i.e. Sharpe *et al.* 1981, Wagner *et al.* 1984). Still, in published articles there is not so much discussion of including temperature-induced mortality in immature life stages and recruitment but both are necessary for more realistic simulation. The complexity of process-based models can range from simplest models with no age structure and limited environmental inputs to age-stage structured or multi-species models with complex environmental drivers. Computer-aided modelling packages such as DYMEX (Kriticos *et al.* 2003) or the "model builder" in the Insect Life Cycle Modeling software (ILCYM, version 2.0, recently developed by CIP) facilitates to compile insect population models. Equations used in process-based models can be based on statistical empirical models. DYMEX does not provide tools to analyse experimental data; parameters for particular equations included in the overall model in DYMEX need to be assessed before by using other statistical packages. ILCYM software provides analytical tools to identify "best-fitting" functions and a broad number of non-linear functions for the diverse applications in insect modelling. Software packages like DYMEX and CLIMEX are not open source products and their costs (about US\$ 4,000) are likely to be unaffordable by research institutions in developing countries. Instead, ILCYM software will be made freely available.

CIP in collaboration with the University of Hohenheim developed a comprehensive temperature-based phenology model for the potato tuber moth *P. operculella* (Sporleder *et al.* 2004), which was validated using field-data derived from several regions (Keller 2003) (special project funded by BMZ). The model provides overall good predictions of population growth potential for the wide range of climatic conditions where the pest prevails today (Sporleder *et al.* 2008). The model is based on the cohort concept of insect populations (Curry *et al.* 1978, Logan *et al.* 1979, Shaffer and Gold 1985, Wagner *et al.* 1985, Logan and Amman 1986) that had been implemented in ILCYM software. Applications of these models are manifold; it allows prediction of population growth potential and interpretation of population dynamics differentiating between various agro-

ecological zones and management practices (Sporleder et al. 2004, 2008, Sporleder et al. 2007c). An important issue in integrated pest management research is to evaluate the potential effects of certain pest management strategies. The current potato tuber moth model provides essential information about the pest population age-stage structure, which makes inclusion of age- or stage-specific mortality factors possible; herewith e.g., the application date and frequency for the potential use of the granulovirus of the potato tuber moth can be predicted that attacks only first instar larvae of the pest (Sporleder and Kroschel 2008). Also, the model can be used for predicting growth potentials for natural enemies of pests (e.g. parasitoids) to determine their potential efficacy or naturalization capacities in classical biocontrol programs. For this, models for specific parasitoids are coupled with the existing pest model in a “two-species-interaction model” (Logan et al. 2006). First attempts have been made with *Copidosoma koehleri*, which is an important parasitoid of the potato tuber moth (Sporleder et al. 2007a). Finally, by linking the phenology model to GIS it offers the opportunity to print maps and to demonstrate and analyze the pest developmental potential for potato regions world-wide and by region in order to support decision-making for appropriate pest management practices (Kroschel & Sporleder 2006) as well as for pest risk assessments (Sporleder et al. 2008) (Annex 3, Fig. 1-4). Both, the phenology model builder and GIS based risk mapping, are components of the ILCYM software. The current model takes temperature as the only influencing variable on insect phenology because these effects are well assessed through laboratory experiments. However, further effects of biotic or abiotic factors should be quantified in future research and included in the model.

Conclusions from completed and ongoing activities for the proposed research

CIP’s research has shown that temperature-based phenology models, as developed by Sporleder et al. (2004), are an ideal tool for assessing climate change effects on insects. For the potato tuber moth, e.g., the model predicted on a global scale a northward expansion of about 400-800 km in the northern hemisphere as well as an expansion to higher altitudes by several 100 m in tropical mountains. Further, the potato tuber moth activity and hence its abundance and severity is very likely to increase in all regions where the pest prevails today (Sporleder et al. 2007) (see Fig. 1 and 2 in annex 3). A regional assessment of the climate change effects in the Andes of Peru showed that the potato tuber moth is distributed today on about 45% of the total potato growing area. For the year 2050, it is predicted that infestation and severity will severely increase on about 45,000 ha of potato and that the moths are likely to invade and establish newly in about 45,000 ha of potato potentially affecting 67% of the total potato growing area in Peru (Beraun and Juarez 2009) (see Fig. 3 in annex 3).

Detailed life-table parameters for insects are the basic data inputs for insect phenology modeling, which can be studied and collected in students’ research programs (e.g., bachelor thesis). However, to make wider use of phenology modeling for IPM planning and other pest risk assessments including climate change, CIP developed user-friendly and freely available software for Insect Life Cycle Modeling (ILCYM Version 2.0) (Sporleder et al. 2008) (BMZ postdoc program); after adapting the software to a wide range of insect pests of different insect orders and families the software will allow scientists of national programs to develop and use temperature-based phenology models, i.e. for forecasting growth potentials of insect pest, evaluate control measures (e.g., define hypothesis for field experiments testing biological control agents), climate change adaptation planning, etc. The potential of GIS combined with insect models is huge; our vision is to combine GIS risk mapping with existing plant models (remote sensing might take part here) for enhanced pest risk analysis. When linked with further socio-demographic data (i.e., population, number of farm families in a region, land use, etc.), ILCYM becomes a powerful tool to analyze the economic, social, and some environmental impacts due to pests, which is an important component of any pest risk analysis.

Biological control of the cassava mealybug and the cassava green mite are landmark examples of successful continent-wide biological control of exotic pest. IITA was at the forefront of both efforts.

The two pests originated from South America and both are widely distributed in Africa where they are under biological control respectively by *Anagyrus lopezi* and *Typhlodromalus aripo*. The distribution, biology and ecology of both pests and their natural enemies are well known and have been documented in more than 200 scientific publications by IITA and its collaborators (e.g., Gutierrez et al. 1999, Neuenschwander 2003, Yaninek and Hanna 2003, Hanna et al. 2005). Considerable information is available for developing robust phenology models, but here is a need to conduct additional life-table studies (e.g., *P. manihoti* and *A. lopezi*) at temperatures higher than what had been used in previous studies to estimate their upper temperature tolerance. Together, the available data and those to be generated by the project will be used to validate present distribution of both pests and their natural enemies, using the CIP ILCYM software program, and to predict the potential for range expansion in Africa as cassava cultivation stretches northward and southward which may affect differently the pests and their natural enemies and may therefore upset existing control of the pests. The Sri Lanka fly, *Bactrocera invadens*, is another invasive species, first detected in Africa in 2003 (Lux et al. 2003). It is now known from 24 countries in sub-Saharan Africa where it has become a major pest of several economically important fruit crops such as mango, citrus, guava, and banana, and numerous wild fruits that are widely consumed in rural sub-Saharan Africa. *Icipe* and IITA (with support from BMZ) have been at the forefront of efforts to stem the spread of this species and develop IPM programs, including biological control, to reduce its impact on major fruit crops such as mango (e.g., Khamis et al. 2008, Rwomushana et al. 2008, Goergen et al., submitted). Moreover, IITA and *icipe* have introduced into Africa (with support from BMZ) a promising parasitoid (*Fopius arisanus*) which has been shown to be highly effective against fruit fly species within the same group to which *B. invadens* belongs (Vargas et al. 2007) and can cause up to 70% parasitism in *B. invadens* (Mohamed et al. 2009). In the proposed project we will attempt to model the establishment in sub-Saharan Africa and its biocontrol potential of *B. invadens*, both under present climatic and climate change conditions.

Identification of the project in relation to the IARC's core projects or programs

The project will contribute to CIPs' MTP 2009-2011 (CIP, 2008): Project 4: Crop Management for Sustainable Intensification of Potato and Sweetpotato Based Cropping Systems, output 3: Components and strategies for the integrated management of potato and sweetpotato pests of global and regional importance and tools for assessing pest risks under climate change and system intensification developed and tested in at least three priority countries per region by 2012; output target: Insect life cycle modeling software (ILCYM) developed and validated for insect species of different orders and families by 2010; output target: Effect of climate change on the phenology and potential efficacy of parasitoids of main potato pests assessed through modeling for adaptation planning by 2011. MTP 2007-2009 (*icipe*): Project 8 Management of staple food pests, the Noctuid graminaceous stemborers, output 1-3. Phylogeny and diversity of afro-tropical stemborers established and interaction between plant and their natural enemies in different agro-ecology documented to allow prediction of host shifts. MTP 2009-2011 (IITA): Roots and Tubers Systems, output 2: Description of biotic and abiotic processes and interactions; Horticulture and Tree Crops; output 1: policy, markets, production constraints, and opportunities prioritized; output 2, environmentally friendly and cost effective technologies developed. "Adaptation to climate change" is defined as one priority theme of the SP-IPM to develop inter-center collaborative research outputs.

Expected use and users of research results

Direct beneficiaries are scientists from NARI and IARC as well as IPM practitioners who apply the project results and modeling tools in their research for developing country specific IPM strategies and for providing appropriate pest management recommendations to policy makers. Final beneficiaries are farmers, especially from Africa, who could profit from more effective and timely provided pest control measures or even from prevention of pest outbreaks due to appropriate

pest management and quarantine interventions. Due to climate change pest associated risks will change, not only in today food insecure regions, but also in industrialized countries and regions. Hence, the methodologies and tools developed by this project and the lessons learned will be of interest for both the scientific and public community at large to better understand and project future effects of climate change on insects in general, which are the most diverse class of organisms on earth providing a range of important functions for the sustainability of natural ecosystems. In this regard, the risk maps developed in this project will provide important information on those pests which could potentially invade agricultural crops in the northern hemisphere. Results may be supportive to strengthen global efforts to alleviate climate change.

Mode of dissemination of research results

The participative research approach envisaged in this project, which is between scientists of three IARC and various scientists from NARI, will contribute to widely disseminating research results in their respective institutions and countries. The first dialog will be established in the two regional training workshops. After the pest climate change scenarios have been prepared, the results will be presented to stakeholders for their evaluation and adaptation planning. In addition, a project webpage will be created to display relevant project information, scientific literature, project publications and the ILCYM software. Further, it is envisaged to widely distribute the "Pest distribution and risk atlas for Africa". Finally, through the SP-IPM the results will be made available to other IARC and national programs. Conventional ways of disseminating research results include annual and final project and workshop reports, publication of PhD and graduate theses, peer reviewed publications, and the presentation of research results at scientific conferences.

Expected benefits of the project for NARI

NARI will benefit by increasing their research capacity to utilize advanced research methods in insect phenology modeling and risk assessment to analyze the vulnerability of agricultural systems to major insect pests under climate change, to identify the need to develop and adapt pest management strategies to climate change and to use and implement this information in national adaptation plans.

3. Project Description and Workplan

A summary of project goal, purpose, outputs and indicators is given in annex 1 (logical frame work); the workplan and timeframe of the project is summarized in annex 5.

Research methodology and procedure

Target pests and associated parasitoids

The target pest species included in the research have been initially selected by participating IARC according to their economic relevance in important agricultural food crops of Africa (Abate et al. 2000), their potential to invade new areas, and in most of the cases are being significantly controlled by indigenous or naturalized (through classical biocontrol) biocontrol agents (for details see table 2 in annex 4). CIP will work and coordinate research on major and invasive potato (potato tuber moth, *Phthorimaea operculella*; leafminer fly, *Liriomyza huidobrensis*) and sweetpotato pests (sweetpotato weevil, *Cylas brunneus* and *C. puncticollis*; sweetpotato butterfly, *Acraea acerata*; whitefly, *Bemisia tabaci*) and associated important antagonists. *Icipe* will target lepidopteran stem borers attacking cereals which include the invasive species *Chilo partellus* and its introduced biocontrol agent *Cotesia flavipes*, the indigenous *Chilo orichalcociliellus*, the noctuid *Busseola fusca* and their parasitoid *Cotesia sesamiae*. IITA will work on cassava mealybug (*Phenacoccus manihoti*) and cassava green mite (*Mononychellus tanajoa*), and the spiralling whitefly (*Aleurodicus dispersus*), which are successfully controlled by the naturalized parasitoid *Anagyrus lopezi*, the predator *Typhlodromalus aripo*, and the pair of *Encarcia dispersa* and *E.guadeloupae*, respectively (D'Almeida et al. 1990, Neuenschwander 2003, Hanna et al. 2005). Both IITA and *icipe* will target the Sri Lanka fly (*Bactrocera invadens*) and its parasitoid *Fopius*

arisanus, which was recently introduced into Africa by icipe and IITA. In workshops, initially organized by the project, participating NARI will decide on which major relevant pests of their mandatory crops they will work as part of this project. We are aiming to evaluate the effect of climate change on different insect orders and families and to develop and provide freely-available software (ILCYM), which will be applicable by national programs for a range of pests and associated natural enemies (Output 5).

Pest distribution, severity and control by associated parasitoids (output1)

Each IARC will review the available data about the present distribution, severity and seasonality of selected key pest species and *associated selected* parasitoids in a particular crop and accordance to climatic data (temperature and rainfall) (Output 1, activity 1.1 and 1.2). Surveys will be carried out on pest severity and the efficacy of parasitoids (parasitism rates) as well as on farmers' present pest management strategies to complete and update data sets (Output 1, activity 1.3 and 1.4). We will select temperature gradients to capture temperature as a major factor to the development of pests and parasitoids.

Phenology modeling and risk mapping (output 2, 3)

Temperature-based phenology models for specific agricultural pests and related parasitoids will be developed using life-table data for pests and natural enemies. In a first step, life-table literature data that might be useful for pest and natural enemy phenology modeling will be reviewed (Output 2 and 3, activity 2.1 and 3.1). However, these data are generally incomplete and do not provide sufficient specific information to model the whole life history of a pest and its associated natural enemy. Additional temperature experiments will be conducted in controlled conditions (incubators, constant temperature experiments) to fill these gaps (Output 2 and 3, activity 2.2 and 3.2). Rearing systems are available for all the pest/natural enemy pairs that are presently targeted. Generally, development time, mortality, sex ratio and reproduction (progenies) will be gathered for temperatures covering the whole range in which the arthropod species can develop (as a minimum in the range between 10 to 35 °C in 5 °C steps) (see Sporleder *et al.* 2004). Experimental design will be species-specific. Life-table studies or cohort-based studies might be employed. For model validation, age-specific life-tables will be also conducted under fluctuating temperature regimes as well as literature data will be used, if available.

Overall phenology models will be established using best-fitting functions in a rate summation and cohort up-dating approach as described by Sporleder *et al.* (2004). Models will be produced with the "model builder" included in the current version of the Insect Life Cycle Modeling (ILCYM) software program (Version 2.0, available at CIP web-site: <http://www.cipotato.org>) developed by CIP. The program provides statistical tools to determine model parameters for specific temperature-process functions and compiles the overall phenology model automatically; however, the predefined model is designed with data of a lepidopteran insect species (*Phthorimaea operculella*) and will require adjustments in the process of the project for other pest species. Resulting models do not simulate phenology only but also provide information about quantitative population biology including reproduction numbers. As one option the program simulates life-tables (input data are daily minimum and maximum temperature) which will be used for model validation, i.e. comparing the simulation results with results obtained from life-table studies under fluctuating temperature (see Keller 2003). Users can choose between deterministic and stochastic life-table simulation. Life-table parameters, i.e. the net reproduction rate, mean generation time, intrinsic rate of increase, finite rate of increase and doubling time are calculated by the program as described in standard biological textbooks (Southwood and Henderson 2000). Through repeated stochastic simulation standard errors for life-table parameters can be obtained. Further validation will be made through comparisons with the current distribution of pests and parasitoids. Deterministic simulation is used to simulate the potential population growth throughout the year. Equal data collection and analysis will be conducted for selected pests' natural enemies. Life-table parameters for a natural enemy simulated over a range of

temperatures compared with results from its host will indicate the temperatures under which the natural enemy will have a higher growth potential than its host and hence might effectively control the pest (Sporleder et al. 2007a). However, population development of natural enemies (parasitoids) strongly depends on the availability of the host. Therefore natural enemy models will be linked with the host insect model in a two-species-interaction model (see Logan et al. 2006). This will allow the understanding of the efficacy of parasitoids at different temperature regimes and provide information on the potential establishment and efficacy of a natural enemy in a region controlling the pest or if annual augmentative releases are necessary to provide control during the cropping season. Workflow charts for the development of the phenology models and the two-species-interaction models are shown in annex 5b.

The phenology model requires daily max. and min. temperatures as minimal inputs and may additionally be parameterised to incorporate rainfall. Risk maps will be produced using GIS implemented into ILCYM software. Assessment of the pest indices on a regional scale simulation (pest risk maps for Africa) will be based on WorldClim data. WorldClim is a set of global climate layers (grids) with a spatial resolution of 30 arc seconds (~1 km², downloadable at <http://www.worldclim.org>) and described in Hijmans *et al.* (2005). WorldClim provides monthly aggregated climate variables. Because this aggregation raises substantial problems of temporal scale, daily max. and min. temperatures will be interpolated for each grid before simulation. While more computationally complex than interpolating point phenology results, this method is considered to provide more flexible and robust results. For higher data accuracy we will use regional meteorological data parameterized by the Max Planck Institute for Meteorology in the framework of the BMZ funded project “Participatory development and testing of strategies to reduce climate vulnerability of poor farm households in East Africa through innovations in potato and sweetpotato technologies and enabling policies”, implemented by CIP (www.cipotato.org/regions/CIP-SSA/ccadaptafrica.html). Three spatially referenced pest risk indices displaying the risk of establishment, numbers of generations per year, and an activity index will be computed for each grid (see example in annex 3, Fig. 1-3). Resulting risk maps will be compared with the real distribution of pests. To predict the species’ future risks due to climate change, similar maps will be generated for different scenarios of climate change. ILCYM presently uses an atmospheric general circulation model (GCM), which has been described by Govindasamy et al. (2003), to forecast global climate for the year 2050 and 2080.

NARI scientists apply ILCYM and identify adaptive strategies

In a first step, the project will initiate training courses for NARI scientists for developing insect life-tables and applying the ILCYM software. Then, MSc. students will be assisted and supervised in studying and developing life-tables, full phenology models and risk maps for the individual pest species selected by the national programs. Analyzed final results of pest risk mapping will then be used to discuss and develop adaptation plans for specific pest problems. This will include defining knowledge gaps for developing new control methods and for providing guidelines to national plant protection and quarantine authorities.

A developmental database to support insect phenology modeling and open-access software ILCYM further improved

The project will develop a huge data set of life-tables for at least 12 pest species and associated natural enemies with various life histories. This database will be used to improve and enlarge the existing ILCYM software (version 2.0) to make it applicable for developing phenology models for almost any insect species. Improved temperature data sets of a high resolution will be integrated and a more user-friendly interactive interface developed for using this software via the internet and to better meet the requirements of the different stakeholders. CIP has developed a World potato and sweetpotato atlas, which distribution maps have been integrated into the ILCYM software to carry out crop specific risk assessments. Further, crop datasets will be incorporated into the ILCYM software for analyzing economic impacts of insect pests.

Inputs, including project staffing requirements

The project requires an Entomologist (German postdoc) experienced in insect modeling for improving and adapting the insect modeling software to various arthropod species. His/her main research is the development, validation and integration of a two-species-interaction model to analyze pest-natural enemy interactions under different climatic conditions. He/she will be based partly in Nairobi at CIP's regional office or at CIP's Lima headquarter. In Africa, he/she will closely coordinate with participating IARC the supervision of NARI scientist including students and will support training in using ILCYM software. This will ensure that life-table data will be correctly and timely determined and provided. In Peru, he/she will work in the Agroecology and GIS team, where he/she will be supported by assistants for GIS, modeling and software development to be hired by the project: One assistant in informatics and statistics will further improve the "model builder" in ILCYM; this comprises to add more options to the model compilation process which might be necessary for some species, to include more functions and options for modeling species reproduction (p.e. changing sex ratios with temperature and age, polyembryony in some parasitoids etc.), develop solutions for the different "two-species interaction" models, and include additional factors in the overall model (precipitation, cultural methods, etc.) (all this might include both implementing statistical tools in R-statistics into the software and linking the final functions used in the proper way for obtaining the overall population model). A second assistant (Java programmer) will be responsible to improve the interface and handling of data in ILCYM. The two assistants will do modifications/sophistications of ILCYM according to the needs of project partners, and software development. Another assistant will improve the GIS tools (climatic data, resolution, interpolation of future temperature according to the GCM used, improve mapping options, etc.). In addition to support from MSc. students to all centers, CIP and *icipe* will be supported by one PhD student each responsible for specific pests or pest-natural enemy relationships. Technicians at all centers will support insect rearing. Main capital inputs are incubators which will be required for establishing the life-table parameter under controlled temperature conditions. The two incubators foreseen in the project will be installed at NARO, Uganda.

At IITA, one technical staff paid by the project will be based at IITA-Cameroon and attached to R. Hanna who will directly supervise the needed laboratory and field research on *B. invadens* and *F. arisanus*. One MSc student will be attached to the University of Yaoundé (Cameroon NARI) to conduct life table studies on *F. arisanus*. R. Hanna – supported fully through IITA contribution - will also supervise, with help from the consultant biodiversity specialist (G. Goergen), the gap-filling and modeling research on cassava mealybug and cassava green mite. Research on spiralling whitefly will be carried out at IITA-Benin facilities by MSc students attached to the Univ. of Abomey-Calavi, and one technical staff supported by IITA contributions. This research – in addition to field surveys - will be supervised by G. Goergen – based at IITA-Benin – who has considerable experience with life tables (subject of his PhD thesis) and is well connected to Benin NARI. Moreover, if data for proposed associations are achieved timely, there is a potential to expand the research to other associations e.g., mango mealybug and its two parasitoids, larger grain borer and its predator *Teretrius nigrescens*, and bean pod borer and its parasitoid *Apanteles taragamae*, – all of which are in culture at IITA-Benin facilities and are major pests of mango, maize, and cowpea respectively.

Roles and responsibilities of the collaborating institutions/partners during implementation

CIP will serve as a project convener and will coordinate training workshops and backstop phenology modeling research with all partners. Further, CIP is responsible for the ILCYM software development and implementation. The initial workshops will be used also for planning purposes to develop an operation plan for the implementation and monitoring of the project. *Icipe* and IITA are responsible for the research carried out at their respective centers and to co-supervise NARI scientists and students. Research by NARI scientists and students will be either

realized at NARI research facilities or at the involved IARC. We envisage that students work concentrated at *icipe* and IITA facilities to optimally use incubators and to facilitate supervision and interaction among all scientists involved. University of Hohenheim will supervise PhD students and will provide scientific advice. Special project agreements between CIP and all partners (IARC and UoH) will be established in which project tasks and responsibility will be clearly defined. As project convener CIP will be responsible for reporting and the publication of the main overall project results such as the “Pest risk and distribution atlas for Africa”. The ILCYM software including the database of developed pest and naturally enemy models will be made available for download on the SP-IPM website. SP-IPM envisages opening a blog on their web site for researcher’s comments and wider discussion of the software and its use. CIP will ensure further up-dating of the software after completion of the project.

4. Probability of Success

The project has a high probability of success since the simulation methodologies and tools (ILCYM model builder and software) for pest risk assessments have been already developed and validated by scientists of the International Potato Center and are made available to this project. However, the tools and methodologies have to be adapted to pests of different arthropod orders and families. Further, the project has to make use of several assumptions and other models projecting climate change temperature scenarios. The need for updating the risk assessments made in this project will be therefore very likely according to new or changing climate change predictions.

5. Training and Scientific Interaction

Enhancing NARI capacity in insect pest modeling and risk assessment is an integral part of the project and incorporated as a specific output. Moreover, NARI scientists will actively contribute to enlarge the project data base on pest risk assessment for Africa. In two training courses – one in East and one in West Africa – scientists of NARI and IARCs involved in the project will be trained by CIP scientists in insect life cycle modeling, which will also identify further target pest species for the climate change studies within this project. Through study visits of scientists from NARI, IARCs and Universities (national universities and the University of Hohenheim) partners training and experience exchange in research methodologies and scientific supervision will be further established. Funding for national and international MSc and PhD students at IARC, NARI and Universities as well as working visits are planned in the budget. In one final workshop climate change scenarios prepared by project partners will be presented and jointly analyzed, and adaptive pest management strategies identified and proposed. Workshop results will be part of the “Pest distribution and risk atlas for Africa” which will be jointly prepared by all partners.

6. Intellectual Property Rights, Biosafety and Genetic Engineering

The research results and products of this project, namely the phenology models, ILCYM software and pest atlas of Africa will be of a patentable or copyrightable nature. However, as a matter of principle, all are considered to be the property of the public domain. In order to ensure that third parties do not use results to claim patent rights for themselves, CIP and its IARC partners will publish the research results as soon as the final versions are generated, and previous research on the applicability of a free copy left license has been conducted. A free copy left license, such as the ones provided by GNU project or Creative Commons, ensures that the works and their derivatives will always be freely available. Should it be determined that a free copy left license is essential to protect the results for public use, CIP will proceed with its registration. Finally, all participants will be recognized with authorships on reports and publications.

7. References

The list of references is in annex 2.

8. Budget (in Euro). See separate excel tables.

Annex 1: Logical Frame work: Summary of project purpose, outputs and indicators

Project: Predicting climate change induced vulnerability of African agricultural systems to major insect pests through advanced insect phenology modeling, and decision aid development for adaptation planning

NARRATIVE SUMMARY	OBJECTIVELY VERIFIABLE INDICATORS	MENS OF VERIFICATION	IMPORTANT ASSUMPTIONS
<p>GOAL: African agriculture (farmers, national agricultural research institutions, policy makers, etc.) copes with the risk of exacerbating and expanding arthropod pests due to climate change and adaptation strategies minimize pest-related major crop losses. .</p>			
<p>PURPOSE: Vulnerability to pests induced by climate change determined through modeling, and a database on temperature-driven phenology models developed and computer-aide tools provided for pest risk mapping and adaptation planning. Scientists and IPM practitioners use the project tools for: country-specific pest risk assessments, adaptation planning, improving their pest management strategies, and for providing information to policy makers to improve national pest management and quarantine programs.</p>	<p>Pest risk atlas for Africa published and insect life cycle model (ILCYM) software used by at least 7 national programs for insect pest risk mapping. National programs use information on pest risks in their climate change adaptation plans.</p>	<p>Final report, publications, PhD and MSc theses, free-available software on the www of CIP and SP-IPM. National adaptation planning documents.</p>	<p>Predicted climate change temperature scenarios are accurate. National programs have the capacity and financial means to develop national climate change adaptation plans.</p>
<p>OUTPUTS AND ACTIVITIES:</p> <p>Output 1: Present distribution of selected target pests and associated natural enemies elaborated according to climatic factors and pest severity with parasitoid efficacy concomitantly determined.</p> <p>Activity 1: Review and map distribution and severity of target pests in different key crops, seasons and agroecologies.</p> <p>Activity 2: Review and map distribution and efficacy of selected natural enemies in different key crops, seasons and agroecologies.</p> <p>Activity 3: Conduct surveys to fill data gaps on pest severity and efficacy of natural enemies in different key crops, seasons and agroecologies.</p> <p>Activitiy 4: Understand farmers' knowledge and coping strategies to control pests.</p>	<p>Literature reviews and compilation of available data on target pest and natural enemy distribution and natural enemy efficacy completed by 12/2010. Surveys completed and survey results available by 6/2011. Survey to capture farmers' knowledge and coping strategies to control pests documented by 12/2010.</p>	<p>Progress reports, survey reports, publications, MSc. theses</p>	

<p>Output 2: Phenology models for highly economic and invasive agricultural pests of global or regional economic importance developed and validated, and their potential to increase infestation and to expand present distribution due to global warming determined.</p> <p>Activity 1: Review and map distribution and severity of target pests in different key crops and seasons.</p> <p>Activity 2: Collect data on temperature-dependent development, mortality, and reproduction of the target pests through reviewing published data and temperature experiments.</p> <p>Activity 3: Develop complete life cycle models (phenology models) using ILCYMs' "model builder"</p> <p>Activity 4: Validated models through published data and life-table studies in different agroecologies.</p> <p>Activity 5: Develop risk maps for current and future scenarios according to temperature modeled by using ILCYM indicating major future pest hot spots.</p>	<p>Life-tables for at least 12 insect pest species under controlled temperatures elaborated by 09/2011.</p> <p>Life-tables validated through fluctuating temperature studies and current distribution information (maps) by 09/2011.</p> <p>Phenology models and risk maps for at least 12 insect pest species using ILCYM software developed by 06/2012.</p> <p>"Pest distribution and risk atlas for Africa" published by 12/2012.</p>	<p>Progress reports, publications, PhD and MSc theses</p>	
<p>Output 3: Phenology models for specific beneficial insect species that are considered strong antagonist of the target pests developed, validated, and linked with the related pest phenology models (two species interaction models).</p> <p>Activity 1: Review and survey distribution and biotic capacity of target pests' natural enemies in different key crops and seasons.</p> <p>Activity 2: Collect data on temperature-dependent development, mortality, and reproduction of selected natural enemies through reviewing published data and temperature experiments.</p> <p>Activity 3: Develop complete phenology models and link with target pest phenology models by using ILCYMs' "two-species-interaction model builder".</p> <p>Activity 4: Validate models through published data, life-table studies under fluctuating temperature and survey results on natural enemy efficacy in different agroecologies.</p> <p>Activity 5: Develop maps indicating biotic capacities of the antagonists for current and future scenarios according to temperature developed by using ILCYM.</p>	<p>Life-tables for at least 8 important parasitoids/predators under controlled temperatures elaborated by 09/2011.</p> <p>Life-tables validated through current distribution and parasitism information by 09/2011</p> <p>Phenology models and pest-parasitoid interaction models for at least 8 parasitoids developed using ILCYM software by 06/2012.</p> <p>Parasitoid distribution and efficacy as part of the "Pest distribution and risk atlas for Africa" published by 12/2012.</p>	<p>Progress reports, publications, PhD and MSc theses.</p>	
<p>Output 4: NARI scientists in pest risks assessments using ILCYM trained and adaptive pest management strategies to cope with new emerging pest problems identified.</p> <p>Activity 1: Organize and conduct in all project regions training workshops on the use of ILCYM software for insect phenology model development, pest risk mapping, and how the software might support</p>	<p>2 training workshops (East-West Africa) performed with a min. of 8 to 10 NARI scientist and target pest species for CC studies identified by 06/2010.</p> <p>Life-tables for at least 10 insect pest species under controlled temperatures elaborated by</p>	<p>Progress reports, publications, MSc theses, information is part of national adaptation plans.</p>	<p>NARI actively participate and support the project.</p>

<p>an overall pest risk analysis.</p> <p>Activity 2: Support and supervise scientists in national programs to conduct pest life cycle experiments and to analyze data using ILCYM.</p> <p>Activity 3: Discuss and develop with national programs adaptive pest management strategies and provide guidelines for adaptation planning to national plant protection and quarantine programs.</p>	<p>NARI scientists by 12/2011.</p> <p>Phenology models and risk maps for at least 10 insect pest species using ILCYM software developed by NARI by 06/2012.</p> <p>Phenology models elaborated by NARI as part of the “Pest distribution and risk atlas for Africa” published by 12/2012.</p> <p>Adaptive pest management strategies and adaptation plans elaborated by 12/2012.</p>		
<p>Output 5: A developmental database to support phenology models for insect pests and their antagonists established and published and the open-access ILCYM software further improved.</p> <p>Activity 1: Establish database within ILCYM and make accessible through the internet.</p> <p>Activity 2: Pest risk atlas under current and future climate change scenarios compiled and published.</p> <p>Activity 3: Temperature databases of current and future scenarios of a spatial resolution of about 1 km² integrated into ILCYM.</p> <p>Activity 4: User-friendly interactive interface developed for using the software via internet (as a tool for pest risk analysis).</p> <p>Activity 5: Add further components that improve the use of ILCYM in Pest Risk Analysis (PRA) (i.e. link a crop database, integrate FAO data for analyzing economic impacts of insect pests, i.e. area of production, yield per ha, number of farmers).</p>	<p>ILCYM software (Final version) adapted to insect pests of different orders and families available by 12/2012.</p>	<p>Software freely available on the www of CIP and SP-IPM.</p>	

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Annex 3: Climate change scenarios for the potato tuber moth, *Phthorimaea operculella*

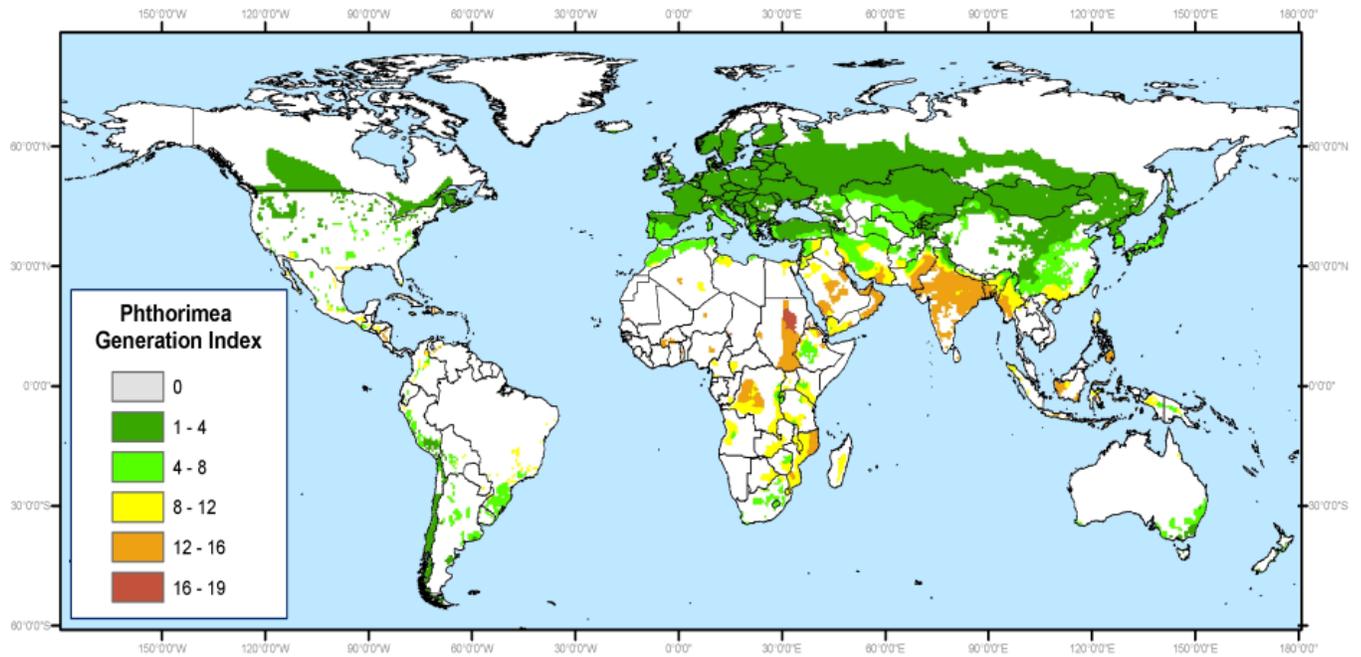


Fig. 1. Generation index (generations / year) for the potato tuber moth under present temperature conditions.

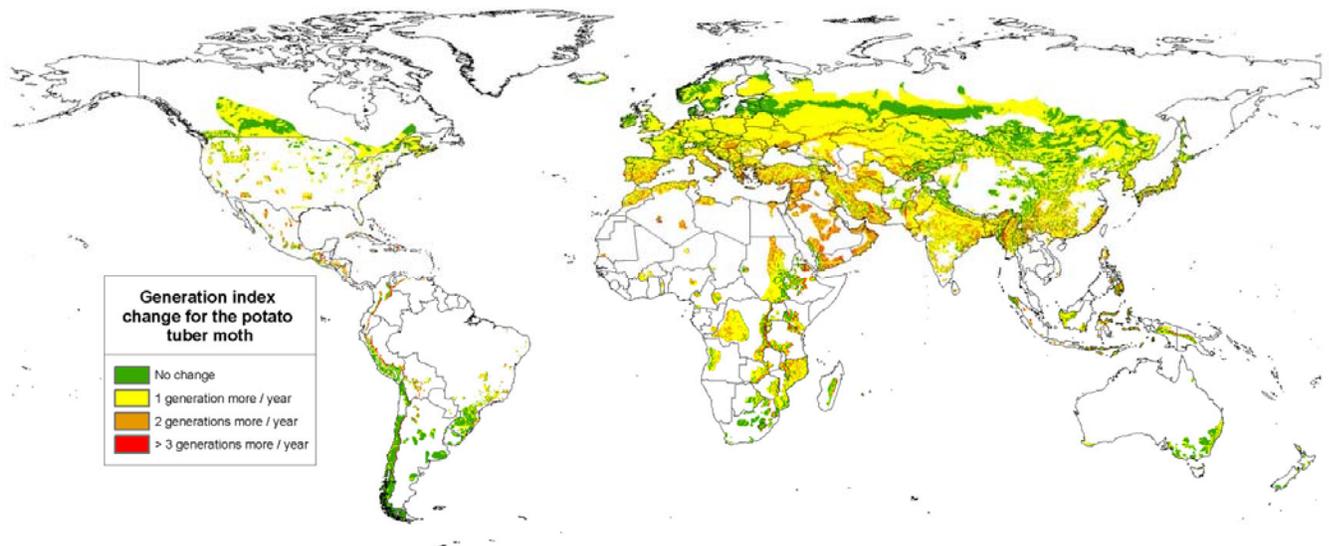


Fig. 2. Change in numbers of generations per year for the potato tuber moth by 2050 using the atmospheric general circulation model by Govindasamy et al. 2003.

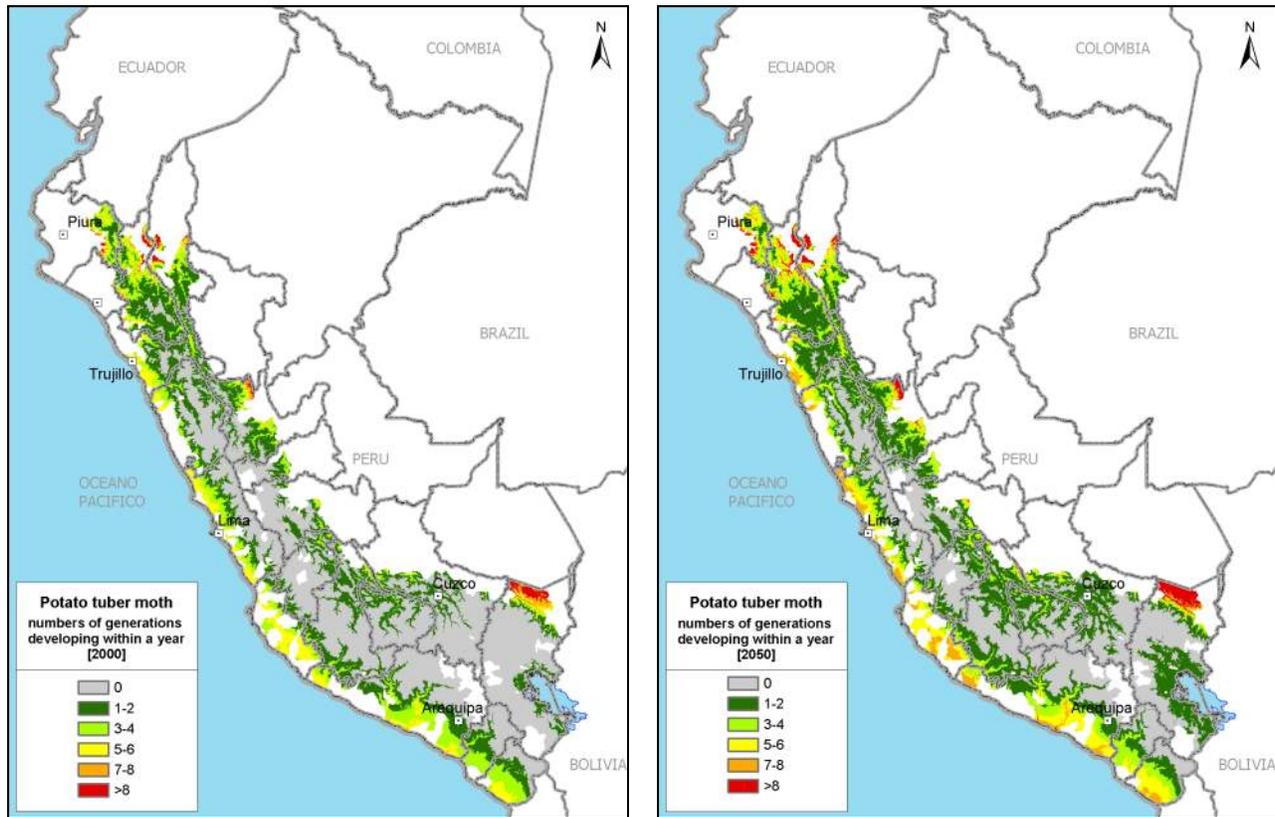


Fig. 3. Generation index (generations / year) for the potato tuber moth under present (year 2000, left) and future (year 2050, right) temperature conditions simulated in Peru using monthly minimum and maximum temperature data for the potato production areas (Beraun and Juarez 2009).

Annex 4: Table 3: Project target pest species and associated parasitoids: status quo of phenology modeling research and project research outputs

IARC	Crops	Target pests	Pest status in Africa	Status of modeling research	Project research outputs	Associated natural enemies	Status of modeling research	Project research outputs	Collaborating partners	
CIP	Potato and other vegetables	<i>Phthorimaea operculella</i>	Exotic	Life-table and modeling complete, maps available worldwide and for some Peru at high resolution	Data collection on current distribution, and pest problem in different agro-ecologies. Regional risk mapping for Africa at high resolution.	<i>Copidosoma koehleri</i> , <i>Orgilus lepidus</i> , and <i>Apanteles subandinus</i>	Life-tables for <i>C. koehleri</i> and <i>O. lepidus</i> complete	Mapping of potential biocontrol efficacy; <i>A. subandinus</i> life-table as part of other project activity		
		<i>Liriomyza huidobrensis</i> , <i>L. trifolii</i> , <i>L. sativae</i>	Exotic	Life-table for <i>L. huidobrensis</i> complete	Life-tables for <i>L. trifolii</i> and <i>L. sativae</i> (2 MSc. or BSc.)	<i>Halticoptera arduine</i> , <i>Chrysocharis flacilla</i> , <i>Phaerotoma scabriventris</i>	Life-tables for all three parasitoids complete	Mapping of potential biocontrol efficacy	KARI, Kenya	
	Sweetpotato	Sweetpotato weevils, <i>Cylas puncticollis</i> and <i>C. brunneus</i>	Endemic	No complete life-table data	Data collection on current distribution and pest problem in different agro-ecologies; life-table and risk mapping (PhD student, Germany)	No parasitoids reported				NARO, Uganda; University of Hohenheim
		sweetpotato butterfly, <i>Acræa acerata</i>	Endemic	No complete life-table data	Life-table (MSc. or BSc.) and risk mapping	<i>Apanteles acraea</i>	No life-table data available	Life-table (MSc. or BSc.) and mapping of potential biocontrol efficacy.		NARO and Makerere University, Uganda
		Whitefly, <i>Bemisia tabaci</i>		No complete life-table data	Life-table (MSc. or BSc.) and risk mapping	<i>Encarsia sophia</i>		Life-table (MSc. or BSc.) and mapping of potential biocontrol efficacy.		KARI, Kenya
	Icipe	Maize, sorghum	Stem borers, <i>Chilo partellus</i> , <i>C. orichalcociliellus</i> and <i>Busseola fusca</i>	Exotic and endemic	No complete life-table data	Life table. Data collection on current distribution, and pest problem in different agro-ecologies. Regional risk mapping for Africa and elsewhere at high resolution.	<i>Cotesia flavipes</i> <i>Cotesia sesamiae</i> (two strains)	Partial life-table data	Life-table and mapping of potential biocontrol efficacy.	IRD, KARI, Kenyatta University, Makerere University

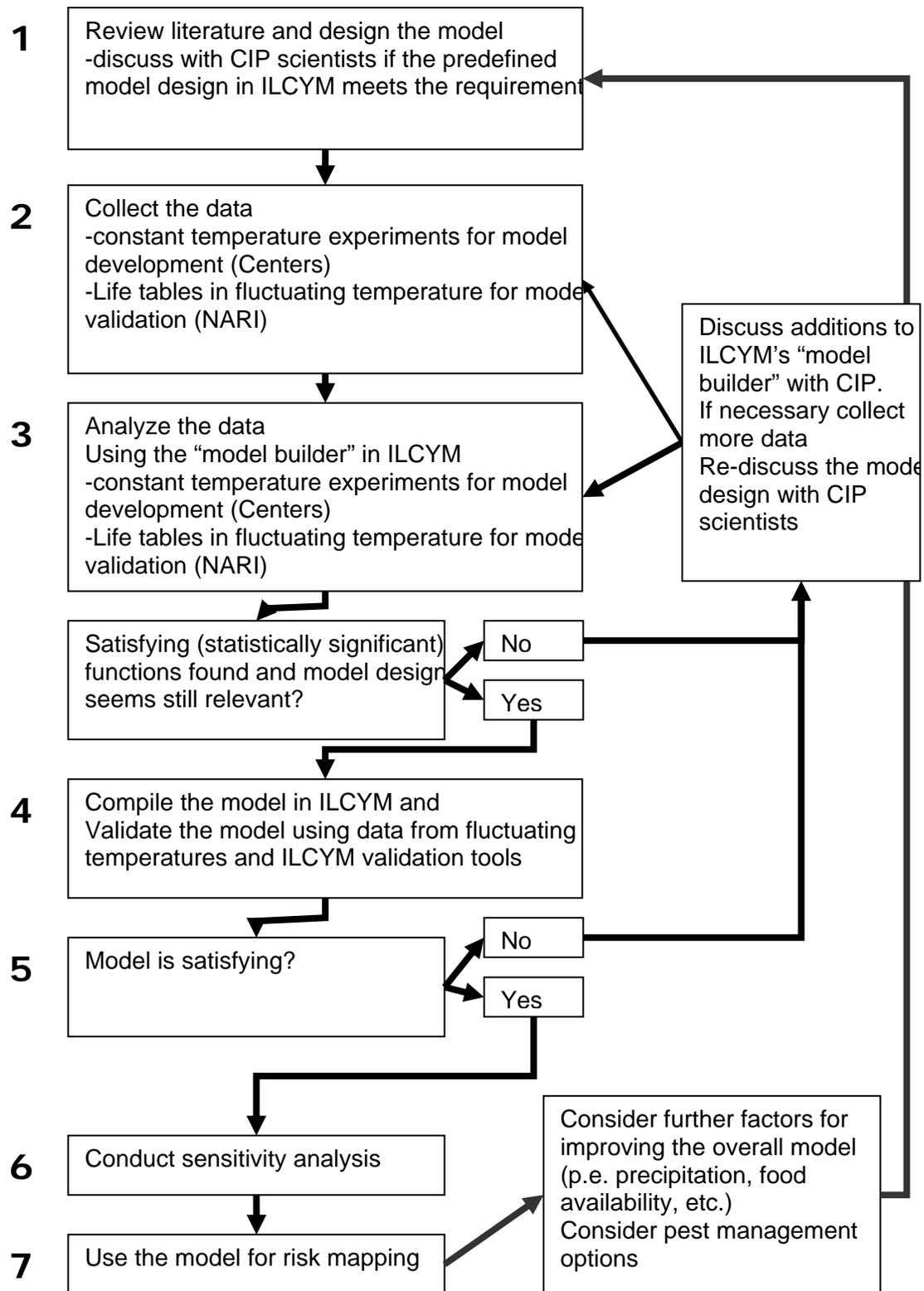
IITA	Cassava	Cassava mealy bug, <i>Phenacoccus manihoti</i>	Exotic	Life table complete	Validation of ILCYM on known distribution and pest status in SSA, including potential colonization where cassava cultivation is expanding	<i>Anagyrus lopezi</i>	Life table complete; two species interaction models available.	Validation of ILCYM on known distribution and biocontrol potential in SSA, including potential colonization and biocontrol potential where cassava cultivation is expanding	CIP
	Cassava	Cassava green mite, <i>Mononychellus tanajoa</i>	Exotic	Life table complete but partially published.	Validation of ILCYM on known distribution and pest status in SSA, including potential colonization where cassava cultivation is expanding	<i>Typhlodromalus aripo</i>	Life table complete but partially published; two species interaction models available.	Validation of ILCYM on known distribution and pest status in SSA, including potential colonization and biocontrol potential where cassava cultivation is expanding	CIP
	Mango, guava, citrus, banana, and many other cultivated and wild fruits	Sri Lanka fly <i>Bactrocera invadens</i>	Exotic	Life table on mango completed and published. Life table on other major hosts needed.	Life table on <i>citrus, terminalia and marula</i> . Data collection on current distribution, and pest problem in different agro-ecologies. Regional risk mapping for Africa and elsewhere at high resolution.	<i>Fopius arisanus</i>	No life table	Life table on <i>B. invadens</i> on mango, citrus, terminal and marula; and Mapping of potential for establishment and biocontrol efficacy.	University of Yaoundé I, <i>icipe</i>
	Cassava, banana, pepper, tomato and numerous other crops	Spiraling white fly <i>Aleurodicus dispersus</i>	Exotic	No life-table data available	Life-table data and risk mapping	<i>Encarsia dispersa</i> <i>Encarsia guadeloupae</i>	No life-table data available	life-table data and biocontrol efficacy mapping	Univ. Abomey-Calavi.

Annex 5a: Work plan and time frame for each activity in each participating country.

CIP in collaboration with	CIP	ICIPE	IITA	University of Hohenheim	NARS	Year 1				Year 2				Year 3				
						1 st quarter	2 nd quarter	3 rd quarter	4 th quarter	1 st quarter	2 nd quarter	3 rd quarter	4 th quarter	1 st quarter	2 nd quarter	3 rd quarter	4 th quarter	
Activities																		
Output 1: Present distribution of selected target pests and associated natural enemies elaborated according to climatic factors and pest severity with parasitoid efficacy concomitantly determined.																		
Activity 1: Review and map distribution and severity of target pests in different key crops, seasons and agroecologies.	X	X	X	X	(X)	X	X	X	X									
Activity 2: Review and map distribution and efficacy of selected natural enemies in different key crops, seasons and agroecologies.	X	X	X	X	(X)	X	X	X	X									
Activity 3: Conduct surveys to fill data gaps on pest severity and efficacy of natural enemies in different key crops, seasons and agroecologies.	X	X	X	X	(X)	X	X	X	X									
Activity 4: Understand farmers' knowledge and coping strategies to control pests.	X	X	X	X	(X)	X	X	X	X	X	X	X	X					
Output 2: Phenology models for highly economic and invasive agricultural pests of global or regional economic importance developed and validated, and their potential to increase infestation and to expand present distribution due to global warming determined																		
Activity 1: Review and map distribution and severity of target pests in different key crops and seasons.	X	X	X	X	(X)	X	X	X	X									
Activity 2: Collect data on temperature-dependent development, mortality, and reproduction of the target pests through reviewing published data and temperature experiments.	X	X	X	X	(X)	X	X	X	X	(X)	(X)	(X)	(X)					
Activity 3: Develop complete life cycle models (phenology models) using ILCYMs' "model builder"	X	X	X	X	(X)			X	X	X	X	X	X	(X)	(X)			
Activity 4: Validated models through published data and life table studies in different agroecologies.	X	X	X	X	(X)					X	X	X	X		(X)	(X)		
Activity 5: Develop risk maps for current and future scenarios according to temperature modeled by using ILCYM indicating major future pest hot spots.	X	X	X	X	(X)									X	X	X	X	
Output 3: Phenology models for specific beneficial insect species that are considered strong antagonist of the target pests developed, validated, and linked with the related pest phenology models (two-species-interaction models).																		
Activity 1: Review and survey distribution and biotic capacity of target pests' natural enemies in different key crops and seasons.	X	X	X	X	(X)	X	X	X	X									
Activity 2: Collect data on temperature-dependent development, mortality, and reproduction of selected natural enemies through reviewing published data and temperature experiments.	X	X	X	X	(X)	X	X	X	X	(X)	(X)	(X)	(X)					
Activity 3: Develop complete phenology models and link with target pest phenology models by using ILCYMs' "two-species-interaction model builder".	X	X	X	X	(X)			X	X	X	X	X	X	(X)	(X)			
Activity 4: Develop maps indicating biotic capacities of the antagonists for current and future scenarios according to temperature developed by using ILCYM.	X	X	X	X	(X)					X	X	X	X		(X)	(X)		

Annex 5b: Working flow charts.

Development of insect pest phenology models



Development of “two-species-interaction” models

