**Predicting the thermal niche of crop pests and diseases under climate change and its implications for food production**

1. **Project Summary**

Availability of food is one of the key components of food security. Published results indicate that the impact of climate change on food security could be significant with a projected range of between 5 million to 170 million additional people at risk of hunger by 2080. Predicting where crop pests and diseases may occur, both now and in the future under different climate scenarios, is a major challenge for crop production, food availability, and indirectly for food security. One possible approach to understand when and where crop pests and diseases could establish and damage food supplies is to estimate the fundamental thermal niche (optimal, minimum, and maximum temperature) of the pests and diseases. To estimate the thermal niche for insects that are pests of crops or transmit pathogens (e.g., viruses) to crops, mechanistic mathematical models will be developed using a Bayesian approach. These models would use life-history traits of vectors (e.g., aphids, psyllids) and pathogens (e.g., Candidatus Liberibacter solanacearum) to estimate measures of disease transmissibility and/or population growth such as the basic reproductive number (*R0*), population growth rate (λ), and the intrinsic rate of increase (*r*). With this information, global thermal suitability maps would be generated showing how many months each location is suitable for a particular crop pest/disease under current and projected climate scenarios. These maps would be useful for crop pest/disease surveillance and for agriculture planning in coming years.

1. **Background information**

Climate change is already affecting crop yields through changes in temperature and precipitation regimes. Studies have shown decreased yields of the top global crops (corn, wheat, rice, and potatoes), which provide most of human caloric intake (Adhikari et al., 2015; Gammans et al., 2017; Ray et al., 2019). Lower yields reduce global food supplies and increase the number of people experiencing food insecurity (Mbow et al., 2019). Climate change also influences the occurrence, prevalence, and severity of crop pests and diseases (Luck et al., 2011). When crop pests and disease outbreaks occur, the impact can be devastating. For example, the Irish potato famine caused by the fungal disease late blight (*Phytophthora infestans*) killed around one million people and a million more emigrated (Kinealy, 2006). More recently, invasions of desert locust (*Schistocerca gregaria*) throughout the Horn of Africa have shown how vulnerable crops are to pests (Salih et al., 2020).

As a result of climate change, temperature has been increasing in the last century. Global warming is projected to alter the distribution of crop pests/diseases, especially of ectotherms (Freeman et al., 2018). Extensive research has established that most species’ physiological and life-history traits respond non-linearly to changing temperatures, increasing from zero at a thermal minimum to a high level at an optimum temperature before declining back to zero at a thermal maximum (Dell et al., 2011). Traits of crop pests/diseases (e.g., survival rate, fecundity) are highly temperature sensitive (Sinclair et al, 2016). Within the range of permissive temperatures, the non-linear influence of temperature on crop pest and disease traits affects the population size, the geographic distribution, and the magnitude of transmission (Bebber et al., 2013). **Determining the effects of temperature on transmission requires identifying temperatures that determine the tradeoffs between different temperature-dependent crop pest and disease traits.**

In the last decade, mechanistic disease models have greatly improved to assess the effect of temperature on vector-borne diseases such as malaria and dengue using life-history traits of vectors and parasites/viruses they transmit. These models allow investigators to estimate rates of transmission and to delineate current and future trends of vectors and parasites they transmit (e.g., Johnson et al., 2015; Mordecai et al., 2019; Villena et al., 2022). A similar approach could be used to assess the impact of changes of temperature regimes on pests (e.g., aphids) and pathogens (e.g., virus, bacteria) they transmit that cause diseases on crops (Figure 1) (e.g., Taylor et al., 2019). For this study, I will focus on the transmission of viruses and bacteria by aphids and leafhoppers, such as the transmission of potato leaf roll virus (PLRV) by *Macrosiphon euphorbiae* in potatoes, the transmission of the maize dwarf mosaic virus (MDMV) by *Myzus persicae* in corn, and the transmission of *Spiroplasma citri* by *Circulifer tenellus* in oranges.

The objectives of the proposed work are to: 1) Use models that include thermal constraints on vector/pathogen physiology to predict where crop pests and diseases will occur (transmission risk), and hence the potential impact on crops as temperature regimes change; 2) Produce current and future crop pest/disease suitability maps based on aforementioned model predictions that can facilitate targeting risk-based surveillance and early pest/disease control strategies to prevent yield losses and food insecurity; 3) Build an open-source database with crop pest and pathogen thermal traits for further research.

The main hypotheses addressed in this proposal are: 1) Increased temperature will enable

crop pests and diseases to establish outside of their existing range; 2) Examining impacts of increased temperatures on crop pest/disease transmission dynamics is key to reducing crop yield losses and promoting increased food security.

1. **Overview of the research plan**

The activities of this research project will be organized in five activities (Table 1). For all activities, the methodology will be developed in general, and then a specific application will be provided for the case of the impact of increasing temperatures in the establishment of crop pests and in the transmission of pathogens by vectors to staple crops.

**Activity 1: Thermal trait data**

Two main sets of data will be aggregated: 1) Thermal responses of crop pests/disease traits (e.g., development rate, fecundity, infection efficiency, etc.) measured across multiple constant temperatures. This data will be collected from published papers, reports, theses (e.g., Chung et al., 2016; Davis et al., 2006) and international crop centers (e.g., International Potato Center – CIP); 2) Temperature across the spatial domain. There is good availability of high spatial resolution global weather data from projects like WorldClim and FEWS NET.

**Activity 2. Build the model and suitability maps**

I propose to utilize a socio-environmental synthesis approach where, from previously published data on thermal responses of crop pest (e.g., aphids) and pathogen (e.g., dwarf mosaic virus) traits, transmission models of pests/diseases affecting top global crops and the current and future transmission risk maps would be produced (Figure 1). First, I would fit a thermal response to each crop pest/disease trait (e.g., development rate) to independent data using a Bayesian approach where Markov Chain Monte Carlo sampling is used to obtain the posterior distribution for each trait (figure 1, step1).

Next, I would incorporate the posterior distributions of each trait into the appropriate mathematical model for the disease systems (e.g., Potato leaf roll disease caused by PLRV and transmitted by the aphid *Myzus persicae*). A common summary of the mathematical models to measure disease transmissibility and/or population growth rate is the basic reproductive number (*R0*), which typically includes the following traits: fecundity (F), proportion of eggs surviving to adulthood (pEA), development rate (DR), mortality rate (MR), vector competence (VC), and extrinsic incubation rate (EIR) (Van den Bosh et al., 2017). Two alternative measures are the population growth rate (λ), which typically uses the following traits in its calculation: F, pEA, DR, MR; and the intrinsic rate of increase (*r*), which uses the following traits for its calculation: F and MR as per capita birth and death rates, and DR (Figure 1, step2).

Next, I would perform an uncertainty analysis for each parameter of the model and for the mathematical model of choice (*R0*, λ, *r*) at each of the temperatures between the range (e.g., 0 °C to 45 °C) of the pest and disease studied (e.g., transmission of the dwarf mosaic virus by aphids). The uncertainty analysis allows for the identification of the traits that contribute the most to the overall uncertainty of the population summary. Lastly, thermal suitability maps for the transmission of crop pests and diseases of the top global crops will be produced based on validated models. The maps will show the number of months per year of suitability for specific crop pests and diseases at current times. Based on the validated models, prediction maps will also be generated, which will show probabilities that some regions would be suitable for crop pests and diseases based on changes on temperature regimes (Figure 1, step 3). These models and maps could be used by governments, policy makers, and agriculture agencies as tools for crop pests and disease surveillance and agriculture planning; and to raise awareness of the impact of climate change on the transmission of crop pests and diseases, which could impact food availability and food security (Figure 1, step 4).

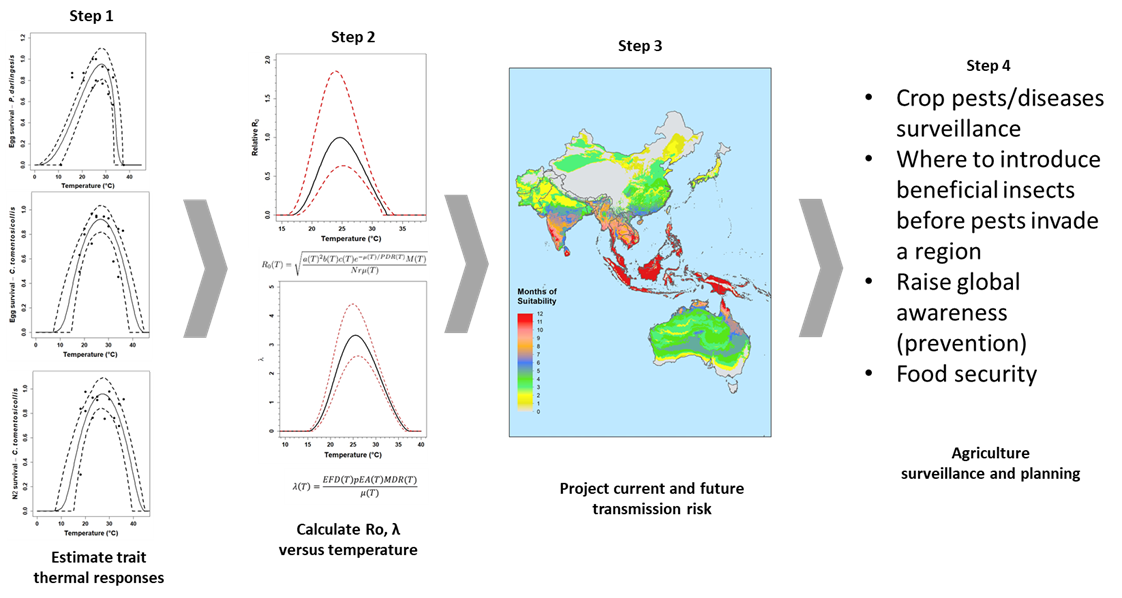


Figure 1: Trait-based model to understand the effects of temperature on crop pests/disease transmission. Step1: thermal performance curves for life-history traits, Step 2: synthesize their combined temperature-dependent effect on *R0*, λ, r, Step3: current and projected suitability maps, Step 4: suggestions for pest/disease surveillance, planning, and prevention measurements.

**Activity 3: Model validation**

Model validation is a critical step in my research to determine applicability in the field (e.g., crop pests’ surveillance). Several potential approaches exist, including the simulation of data from mechanistic models or testing the accuracy of models fit to training dataset when predicting a separate testing dataset (Fordham et al., 2017; Yates et al., 2018). But few studies have applied existing methods to validate pest and disease models. To validate the models, I would compare the model predictions to other models (e.g., species distribution models - SDMs) and see how similar they are. I would also compare our model predictions to independent field data (Hooten and Hobbs, 2015).

The Earth Commons Institute at Georgetown University would play a key role in the development of this proposal through 1) the mentorship of Dr. Arab and Dr. Armbruster because of their expertise in statistics, community and ecosystems responses to climate change as well as in insect and invasive species. Dr. Arab research focus on Bayesian statistics, Infectious diseases, epidemiology, and environmental studies. Dr. Armbruster research focus on life-history traits underlying adaptation to changes in the environmental conditions, as well as factors that facilitate or constrain adaptive evolution; 2) the expertise of the diverse group of researchers and postdoctoral fellows at the Earth Commons Institute; 3) the use of high-performance computing and website to host the crop pest and disease thermal traits; 4) the potential for interinstitutional coordination with the international crop centers to obtain information about the effect of temperature on life history traits of crop pests.

The Earth Commons Institute would be an excellent place for me to continue my scientific career. Moreover, I would contribute to the Institute’s mission by developing models that provide vital information about the impact of climate change on crop pests and diseases that could be used for real-world decisions for policymaking, climate adaptation and mitigation practices, and a more sustainable planet. The expected products of this proposal would be two manuscripts: (1) Thermal limits for the transmission of the potato leaf roll virus by *Macrosiphon euphorbiae* and for the transmission of the maize dwarf mosaic virus by *Myzus persicae* and (2) Thermal niche for the transmission of *Spiroplasma citri* by *Circulifer tenellus* and its impact on the orange industry. In addition, I would present results in conferences and would design and teach a course/workshop to share/teach how these models are implemented and how this approach could be applied to other vector-pathogen systems for which sufficient trait data of both vectors and pathogens exist.

**Activity 4: Generalize findings and develop recommendations**

Findings of the research and derived recommendations would be published in high impact scientific journals. The research team would also present the results and recommendations of the study in national and international conferences.

**Activity 5: Broader Impacts**

Results and recommendations of the project would be use in the elaboration of prevention plans by local, regional, and national governments. The developed database would be available trough a repository for further research by other organizations. An R package would be developed with the functions and models used in the research for a broadly use by universities, research institutions, agriculture agencies, and other organizations.

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|  | **First year** | | | | | | | | | | | | **Second year** | | | | | | | | | | | | **Third year** | | | | | | | | | | | |
| **Activity 1** |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| **Activity 2** |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| **Activity 3** |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| **Activity 4** |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| **Activity 5** |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| **Reports** |  |  |  |  |  |  |  |  |  |  |  | **X** |  |  |  |  |  |  |  |  |  |  |  | **X** |  |  |  |  |  |  |  |  |  |  |  | **X** |

Table 1: Timeline for project activities.

1. **Biographical Sketch (Appendix)**
2. **Postdoctoral Mentoring plan**
3. **Budget**

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