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Predicting the impact of climate change on regional and seasonal abundance of the mealybug *Phenacoccus solenopsis* Tinsley (Hemiptera: Pseudococcidae) using temperature-driven phenology model linked to GIS

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ABSTRACT

The mealybug *Phenacoccus solenopsis* Tinsley (Hemiptera: Pseudococcidae) is a highly invasive and polyphagous pest of global incidence. The fundamental hypothesis of the present study was that the temperature variations due to global climate change may affect seriously the future distribution and abundance of *P. solenopsis*, which might further aggravate the crop yield losses. We employed a temperature-based phenology model of *P. solenopsis* in a geographic information system for mapping population growth potentials of *P. solenopsis*. The three risk indices *viz.*, establishment risk index, generation index and activity index were computed using interpolated temperature data from worldclim database for current (2000) and future (2050) climatic conditions. The daily minimum and maximum temperature data from four selected weather stations in India were used for analysing within-year variation of pest population. A linear relationship was established between the activity indices and yield losses at various locations reported in literatures for predicting the future trend of yield loss due to climate change. The results revealed that, under current temperature conditions *P. solenopsis* can complete >4.0 generations per year on ~80% of the global cotton production areas. Economic losses are likely to occur in areas where at least 8.0 generations can develop in a year; under current climate ~40% areas fall under this category. The increased geographical suitability at higher latitudes in cotton production areas, additional 2.0 generations per year, and 4.0 fold increase of population abundance of *P. solenopsis* are expected in tropical and sub-tropical cotton areas of Brazil, South Africa, Pakistan and India due to predicted climate change. Analysis of within year population increase at various selected locations in India revealed that, *P. solenopsis* attained maximum potential population increase during the major cotton growing season (May–June to October–November). On the other hand, the innate ability of *P. solenopsis* population to increase reduced considerably during off season and cooler winter months. The increased pest activity of *P. solenopsis* due to climate change may intensify the losses in cotton yield, with forecasted losses in India to increase from existing losses of million US$ 1217.10 to future losses of million US$ 1764.85 by the year 2050. Here, we illustrate the possible impact of climate change on future *P. solenopsis* exacerbation based on temperature-driven population studies, which will help in undertaking agro-ecoregion specific management strategies.

1. Introduction

The global climate change is predicted to raise the mean surface temperature of earth by 1.1 to 6.4 °C by the end of 21st century. This may exacerbate the already serious challenges to food security and economic development of the human societies (IPCC, 2007). Pest menace is one of the limiting factors to the agricultural

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productivity. Inspite of several crop protection measures, arthropod pests are reducing the crop production substantially, with estimated worldwide yield losses to the tune of 16–18% (Oerke, 2006). Being poikilotherms, insects have very limited ability of homeostasis with external temperature changes and hence, temperature is the major abiotic factor influencing insect's life cycle. Impacts of climate change on insect pests of agricultural crops have received considerable attention globally. Expansion of geographic ranges at the higher latitudes and altitudes (Porter et al., 1991), increase in number of generations per year due to accelerated growth rates and shorter generation times (Yamamura and Kiritani, 1998), increased risk of introducing invasive alien species (Ward and Masters, 2007), and increase in overwintering survival due to milder winters (Bale and Hayward, 2010) are some of the predicted impacts of climate change on insect pests of agricultural crops. The tropical and sub-tropical regions of the world are more challenged with the impacts of looming climate change and the resultant pest outbreaks because of the year-round favourable climatic conditions for food availability and pest multiplication.

The pest forecasting models facilitate better preparedness to combat outbreaks of serious insect pests by developing effective pest management strategies well in advance. The temperature-response phenology models simulate the variability in insect development times within a population based on the detailed laboratory assessments of the insect's life history and thus, can provide better results on future pest activity (Wagner et al., 1984). Spatial simulations of phenology models using algorithms in geographic information system (GIS) allow prediction of pest population dynamics in different agro-ecological regions in response to climate change (Kroschel et al., 2013).

The mealybug, *Phenacoccus solenopsis* Tinsley (Hemiptera: Pseudococcidae) is a highly invasive pest of cotton, vegetables and ornamentals. *P. solenopsis* is native to North America (Williams and Granara de Willink, 1992), and is currently widespread in more than 24 countries worldwide causing significant crop losses (Ben-Dov, 1994; Abbas et al., 2005; Akintola and Ande, 2008; Nagrare et al., 2009; Wang et al., 2010). It has recently caused devastating outbreak on cotton in India (Jhala et al., 2008; Nagrare et al., 2009) and Pakistan (Abbas et al., 2005; Arif et al., 2012). Estimated yield losses to the cotton due to *P. solenopsis* damage in India were 30–40% (Dhawan et al., 2007; Nagrare et al., 2009). The fundamental hypothesis of the present study was that the temperature variations due to global climate change may exacerbate *P. solenopsis* abundance and damage, which might further aggravate the crop yield losses. This has led to a need for reliable data to help establish and underpin realistic population growth and damage potentials of *P. solenopsis*, along with the formulation of acceptable and robust policies for adaptation and mitigation under changed situations. Hence, the study employed *P. solenopsis* phenology model (Fand et al., 2014) in a GIS environment to examine the changes in its activity at current and future climatic conditions using climate data from worldclim at a resolution of 10 arc minutes for global and 2.5 arc minutes for regional mapping (Hijmans et al., 2005).

2. Materials and methods

2.1. Temperature-driven phenology model for P. solenopsis

A temperature-based phenology model of *P. solenopsis* (Fand et al., 2014) was employed in a GIS for mapping its population growth potentials. The model predicts potential population increase of *P. solenopsis* within a temperature range of 15–40 °C, with 25–35 °C as the favoured temperature range. The model consists of a set of functions that describe the temperature-dependent development in the immature life stages and the senescence in the adult stages. The reproduction was modelled using temperature-dependent oviposition and age-specific fecundity rate. The functions and the parameters used to describe the development, mortality and reproduction are presented in Table 1 (Fand et al., 2014).

Table 1
Parameter values of the functions used for simulation of temperature-dependent phenology of *P. solenopsis* (for explanations on parameters of functions used, see Fand et al., 2014).

Development and its distribution

Life stage	Development time (cumulative distribution function)		Life stage	Development rate (Sharpe and DeMichele Model)				
	Function fitted	Slope		P	T_o	H_a	H_h	T_h
Nymph 1	Probit	12.22	Nymph 1	0.240	307.01	11,215.74	220,244.25	316.98
Nymph 2	Probit	13.43	Nymph 2	0.200	307.62	9581.10	226,302.90	317.35
Nymph 3	Cloglog	12.05	Nymph 3	0.105	290.03	10,342.98	164,117.57	316.81

Mortality of immature life stages

Life stage	Wang equation			Life stage	Exponential polynomial function		
	Topt	B	H		a (intercept)	b	c
Nymph 1	27.10	5.29	0.086	Nymph 3	1.25	−0.302	0.006
Nymph 2	25.40	4.36	0.021				

Mean senescence rates for adult life stages

Life stage	Stinner equation					Life stage	Tanigoshi equation			
	c_1	c_2	k_1	k_2	T_o		a_0	a_1	a_2	a_3
Female	42.26	15.50	3.58	0.216	25.14	Male	0.652	−0.047	0.002	0.000

Temperature-dependent reproduction

Parameter	Gaussian denominator				Parameter	Age-specific oviposition rate		
	a	b	c	d		a	b	c (Intercept)
Fecundity	−0.996	4273.98	28.84	−9016.75	Cumulative oviposition rate	−0.156	0.198	3.2