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Full Length Research Paper

Leafminer agromyzid pest distribution over Limpopo province under changing climate

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The objective of the study was to assess the impact of climate change on the spatial distribution of leafminer agromyzid pest over Limpopo province, South Africa. In the study the Conformal Cubic Atmospheric Model (CCAM) simulated climate scenarios; (a) the current climatology (1981-2010), (b) projected near future climatology (2041-2070) and (c) the projected distant future climatology (2071-2100) was used. In particular, the linkage between the model simulated temperature and the pest population parameters (that is, the intrinsic rate of increase (rm), net reproduction (ro), mean generation time (tg)) was modeled by empirical functions based on laboratory temperature measurements. The empirical functions (derived from the correlation between temperature and rm, o as well as tg) are used to simulate spatial distribution of leafminer agromyzid pest under changing climate. The present analysis illustrates that leafminer agromyzid pest and climatic factors exhibit a non-linear relationship best described by polynomial function of order two while in general, the influence of climate change on the spatial distribution of leafminer agromyzid pest over Limpopo province is noticeable. This work contributes towards our understanding of the impact of climate change on the population dynamics of leafminer agromyzid pest and hence impacts on tomato production in Limpopo province, South Africa.

Key words: tomato pests, leafminer, climatic variables, Limpopo province.

INTRODUCTION

The polyphagous leafminer agromizyd pest continues to depict high adaptability, invading many countries and causing damage to many crops (Costa-Lima et al., 2010; Yıldırım and Ünay, 2011), despite the varied inherent ecosystems. In particular, tomato crop (which is an important vegetable globally) is among the many crops which are damaged by the leafminers. The tomato crop (*Lycopersicon esculentum*) is grown around the world, both outdoors and under glass, for fresh market consumption and for processing. It requires protection from a variety of pests, including pathogens, weeds, nematodes, and insects and other arthropods (Lange and Bronson, 1981). Leafminers have a relatively short life cycle. The time required for a complete life cycle of leafminers in warm environments is 21 to 28 days, so various generations can occur annually in tropical climates. Leibee (1984) determined the growth cycle of leafminers at a constant of 25°C, and reported that about 19 days were required from egg deposition to emergence of the adult.

Development rates increase with temperature up to about 30°C, thereafter further increases in temperature becomes detrimental to the growth of leafminers and larvae experience high mortality. Minkenberg (1988) indicated that at 25°C the egg stage required 2.7 days for development, the three active larval instars required 1.4, 1.4 and 1.8 days, respectively and the time spent in the puparium was 9.3 days. Also, there was an adult preoviposition period that averaged 1.3 days. The temperature threshold for development of the various stages after the oviposition period is 6 to 10°C except that laying of eggs required an average temperature of

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12°C (Minkeberg, 1988).

As reported by Kocmankova et al. (2008), climatic and weather conditions during the different seasons are the main factors influencing the intensity and the occurrence of pests. Climatic factors such as temperature, precipitation, humidity, wind speed and direction directly influence pest distribution and growth by affecting their rate of development, reproduction, distribution, migration and adaptation. Furthermore, indirect effects can occur through the influence of climate on the insects' host plants, natural enemies and inter-species interactions with other insects (Porter et al., 1991).

Additionally, temperature and water availability are among the most important abiotic factors that can influence insect abundance and distribution (Chown, 2002). Temperature tolerance has been the most studied among polyphagous leafminers and was the subject of a recent review by Kang et al. (2009). As reported by Lange and Bronson (1981), managing insect pests at a regional scale is very difficult and complex. Furthermore, forecasting insect pests in space and time in heterogeneous landscapes requires updated knowledge of pest population levels and their position in the managed space, and an estimate of their future population levels and the way their surrounding habitat may affect their levels (Horowitz and Ishaaya, 2004).

Several studies that predict pest distribution have been reported in the literature. Aragon and Lobo (2012) used a previously developed protocol designed to estimate the climatic favourability of the western corn rootworm (WCR) (Aragòn et al., 2010 for further details on the protocol) and derived potential distributions of WCR for current and future climatic conditions. Their results demonstrated that a northward advancement of the upper physiological limit was linked to climate change, which might increase the strength of outbreaks at higher latitudes. Hlásny et al. (2011) used the PHENIPS model to evaluate climate change impacts on the distribution and voltinism of spruce bark beetle in the Czech Republic. Further, Estay et al. (2008) used simple models, such as Ricker's classic equation to study the predictive capacity of the dynamic behaviour of insect populations. Ghini et al. (2008) assessed the potential impact of climate change on the spatial distribution of coffee nematodes (races of *Meloidogyne incognita*) and leafminer (*Leucoptera coffeella*), by using a Geographic Information System.

In this study, we examined the potential geographical distribution of the leafminer agromyzid pest under a range of climate change scenarios using an insect population model. Different pest population parameters (a) intrinsic rate of increase (r_m): this is the rate of increase per head under specified physical conditions in an unlimited environment where the effects of increasing density do not need to be considered (Birch, 1948), (b) the net reproductive rate (R_o): this is the rate of multiplication in one generation (Lotka, 1945), and (c) the mean generation time (t_g) which is the average time elapsing from reproduction in one generation to the time the next generation reproduces (Chubachi, 1979). In this present work, temperature was considered as the most important climatic factor because it is the key environmental driver of the development of the insect's life cycle (Edelson and Magaro, 1988; Harrington et al., 2001). Temperature is also a climatic variable whose future changes are estimated with a good measure of confidence (Houghton et al., 2001).

The aim of this present analysis is to investigate the linkage between the leafminer population parameters and temperature over Limpopo province (because it produces the highest proportion of tomato to the southern Africa market) based on the dynamically downscaled climatic factors under the present, near and distance future climate scenarios of some selected GCMs by (a) assessing the climatic influence on the spatial distribution of leafminer over Limpopo province, (b) use the empirical relationship between temperature and certain population parameter to project future distribution of leafminer in Limpopo province based on the projected temperature scenarios.

MATERIALS AND METHODS

Study area

Limpopo province is situated in the north of South Africa about 22 to 25°S, 27 to 32°E (Figure 1). There are three distinct climatic regions over Limpopo province, that is, the Lowveld, Highveld and Middleveld climatic regions. The province experiences summer rainfall with warm to hot summer temperatures and cool winters. The Lowveld region can be characterised by hot and dry conditions, with no frost and an average rainfall of 450 mm per annum. Additionally, the province has a few high potential areas for dry land crop production and many opportunities for extensive ranching and irrigated fruit and crop production.

The drier lands in the western and northern parts of the province are mainly devoted to extensive livestock farming and game ranching with cropping and mixed farming enterprises in the better areas. More intensive commercial field crop farming is mainly confined to the south central plains. The north-eastern region of the province is characterized by subsistence farming. Susceptibility to drought and the scarcity of water pose a threat to stability and future development of agriculture in the Province. Agriculture nevertheless remains vital for the future well being of the economy of the Northern Province.

The site for this study was selected because Limpopo province is a main tomato growing area in South Africa, producing 66% of the total annual tonnage of tomatoes (NDA, 2009). Leafminer pest is also one of the major pests attacking tomato crop and capable of causing the major yield reduction on tomato production and the control of leafminer poses serious challenges due to its biology and quarantine, and variations in temperature strongly affect the insects' physiology, phenology and spatial distribution (Harrington et al., 2001).

Data

The climatic data used in this study were obtained from the Circulation Cubic Atmospheric Model (CCAM) developed at the

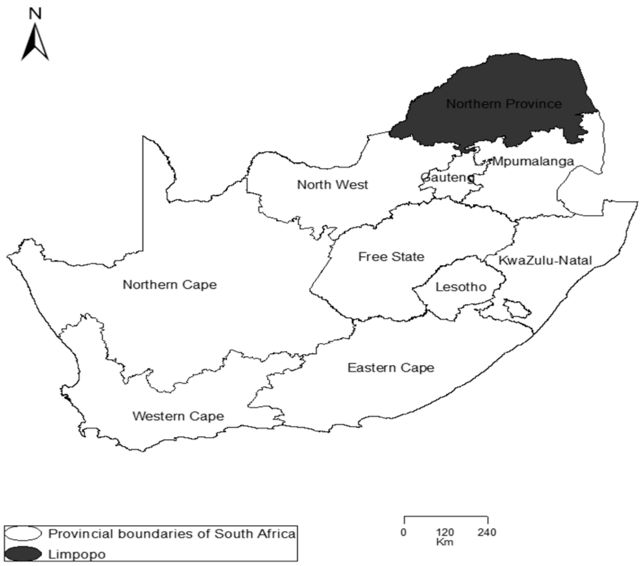

Figure 1. Limpopo province of South Africa.

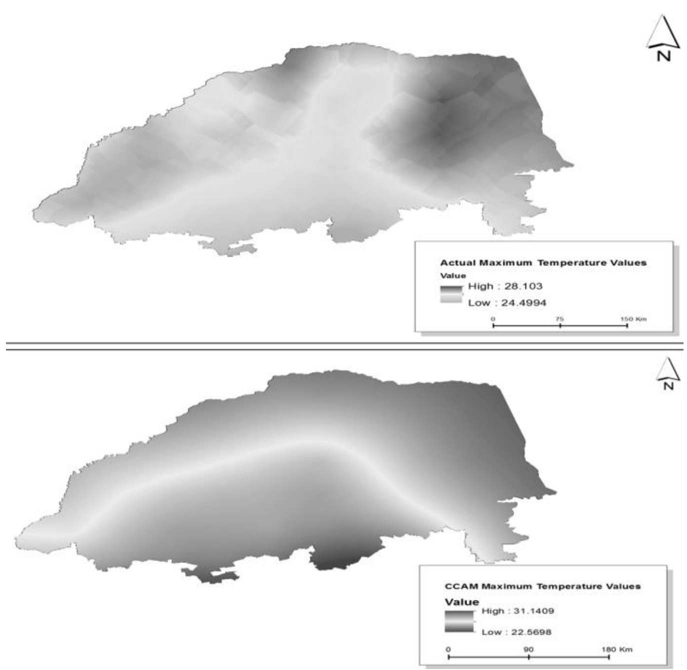

Figure 2. Differences between maximum actual temperature value and CCAM temperature values in degree Celcius (˚C).

Commonwealth Scientific and Industrial Research Organization (CSIRO) Marine and Atmospheric Research in Australia (McGregor, 1996). More details on the geometrical aspects and dynamical features of CCAM can be found in McGregor (2005). The CCAM data sets were validated before they could be used to simulate the distribution of the pest. In the validation process considered in this present study, temperature measurements (hereafter observations) were extrapolated to CCAM grid by using the method of cubic weighted averaging. The purpose of the validation was to assess the representativeness of the CCAM data sets. As depicted in Figure 2, the range of the differences between the CCAM temperature data and the actual temperature data is less than 3.5°C with a 1.985 standard deviation (SD). The grid resolution of CCAM is course since the area under consideration is quite small and therefore it is expected that the temperature fields be homogenous as much as possible, and hence the small value of the difference in temperature. Furthermore, based on the visual interpretation of Figure 2, the spatial distribution of temperature field across this study area is smooth due to the spatial averaging. There is however a noticeable south-north positive gradient in the temperature field (Table 1).

Laboratory measurements of temperature as climatic variables used to model the empirical relationship between temperature and some selected populations parameters of the pest were adopted from Zhang et al. (2000). Thereafter, the pest model parameters were established: these were the empirical functions (that is, the polynomial functions) of the population parameters. Furthermore, a statistical analysis was carried out using Statistica version 10; the effect of temperature on the variables was tested by linear regression and the differences in population parameters were compared using regression analysis.

Pest model development

Pest model used in this present study considered three population parameters of leafminer population dynamics were considered, that is, r_m, r_o and t_g. For further quantitative information (expressions) on the population parameters, refer to Birch (1948). The focus of this present analysis was to investigate the linkage between population parameters and temperature over Limpopo province based on the dynamically downscaled climatic factors under the present, near and distance future climate scenarios of some selected GCMs. Empirical functions (Table 2) derived from laboratory measurements reported by Zhang et al. (2000), and presented in Table 1 are used to build the relationships between the climatic factors and the selected leafminer population parameters.

As depicted in Table 2, simple and parsimonious second-order polynomial function could be used to sufficiently describe the empirical relationship between temperature and the selected population parameters. As illustrated in Table 2, the most significant terms (coefficients A, B and C) of the empirical functions exhibit different values across the population parameters. The coefficients A, B and C characterize the linkage between temperature and population parameters. In particular, the linear relationship between temperature and population parameters is described by coefficient B while the non-linear relationship between temperature and population parameters is accounted for by coefficient C. Coefficient A is constant and also accounts for the outliers in the model.

RESULTS

Intrinsic rate of increase of leafminer agromyzid under present, near- and distant future climate change scenarios

From our analysis, the effect of temperature on the intrinsic rate of increase (r_m) parameter under the present climate change scenarios during the period of 1981 to 2010 was not significant (that is, for example, R^2=0.6682; pvalue 0.0572). The spatial distribution of normalized r_m values based on the dynamically downscaled GCMs by CCAM over Limpopo province under the present climate

Table 1. Statistics of the CCAM simulation and the observations.

Statistics	Max.	Min.	Mean	STD	R^2	RMSE
CCAM simulations	31.14	22.56	28.20	1.96		
Observations	26.07	25.7	25.92	0.067	0.55	3.011
Differences	3.94864	1.73632	2.28	1.893		

Table 2. Population parameters of leafminer in five temperature treatments (Zhang et al., 2000).

Temperature (°C)	Intrinsic rate of increase (r_m)	Net reproductive rate (r_o)	Mean generation time (t_g)
15	0.0374	5.1331	43.7
20	0.1297	66.9149	32.4
25	0.2199	112.8628	21.5
30	0.2667	116.819	17.8
35	0.2192	26.5109	14.9

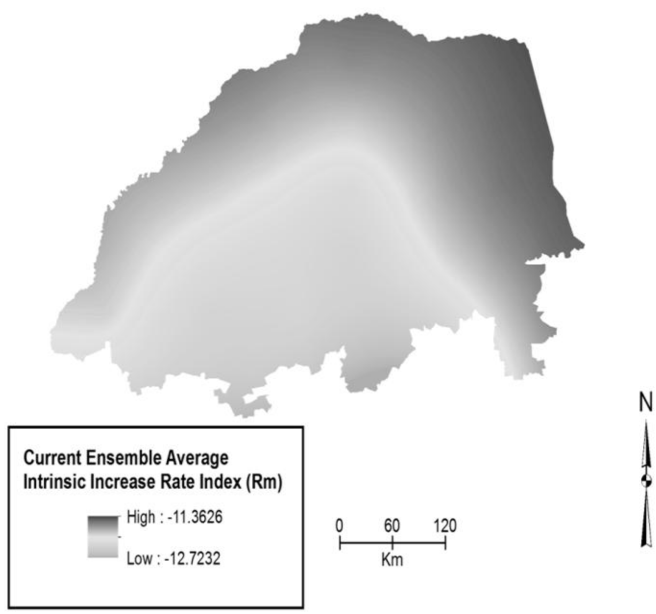

Figure 3. Intrinsic rate of increase (rm) of leafminer agromyzid under present climate change scenarios (1981-2010).

change scenarios (1981 to 2010) is depicted in Figure 3.

From the current temperature data, it can be observed that during 30 year period investigated in this study, southern parts of Limpopo province experienced optimal temperatures which are favorable to the rate of a population increase. As depicted in Figure 3, using the median (-11.36) as a threshold value, a high proportion of this study area has a higher value of r_m (~75% of the study area is covered by r_m values which are greater than the median) implying that temperature variability of the current climate change scenarios will most likely affect r_m. The analyses suggest a substantial increase in the pest population over the Limpopo province, which is more pronounced along the northern border.

As illustrated in Figure 4, the intrinsic rate of increase corresponding to the near future climatic period (2041 to 2070) exhibits an optimal temperature of 30°C in the region towards the South of Limpopo province and this condition are favorable for increasing the pest population in the near future. Notwithstanding the optimal temperature during over the near future climatic period, our analysis demonstrate that a large proportion of this study area has a low values of r_m implying that temp-erature variability of the near future will not likely affect r_m.

Normalized r_m index in the distance future 2071 to 2100

The spatial distribution of the normalized r_m index as derived from distance future temperature over Limpopo as depicted in Figure 5 illustrates that a large proportion of this study area has a high values of r_m. This suggests that temperature variability of the distance climate period as simulated by CCAM will not likely influence the pest population. As illustrated in Figure 5, the high proportion of this study area has a high value of -11.1473 and the rest of this study area has the low value of -12.9792. The r_m distant future has a standard deviation (SD) of 0.445. The r_m difference between the current, near future and distance future is -0517.

Net reproduction rate of leafminer under present, near- and distant future climate change scenarios

The effect of temperature was not significant between the different constant temperature and the net reproduction rate (r_o) (see p-value 0.0633; R^2=0.0854). As depicted in Figure 6, temperatures could have a dominant influence on the rate of multiplication of leafminer generations during

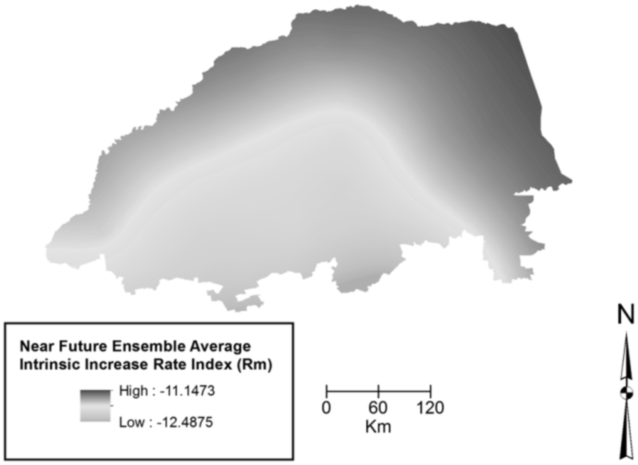

Figure 4. Intrinsic rate of increase (rm) of leafminer under near future climate change scenarios (2041-2070).

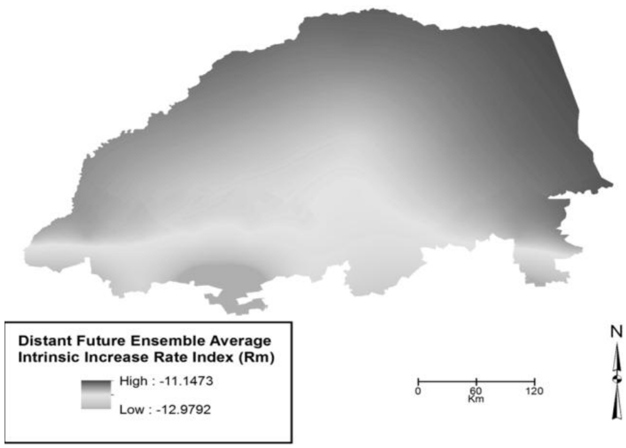

Figure 5. Intrinsic rate of increase (rm) of leafminer under distant future climate change scenario (2071-2100).

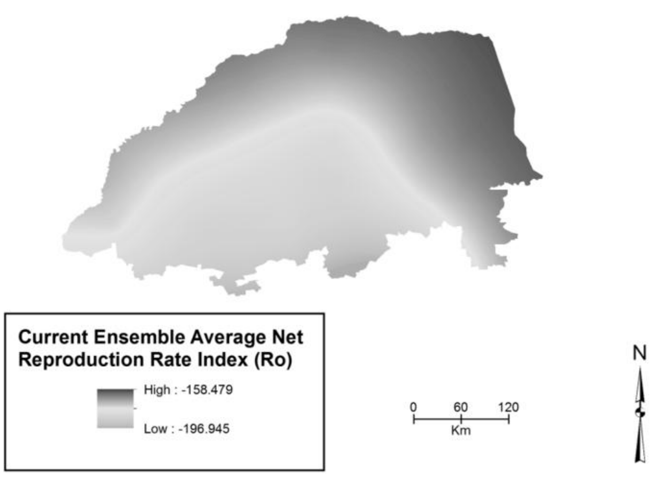

Figure 6. Net reproduction rate (ro) of leafminer under present climate change scenarios (1981-2010).

1971 to 2010 over the Southern parts of Limpopo, while the temperature changes would have a negative response to r_o over the northern, eastern and western part of Limpopo.

In general, the projected distribution of normalized r_o of leafminer in the current climate change scenarios during 1981 to 2010 over Limpopo shows high rate of multiplication of each generation where the temperature was high. In particular, Figure 6 demonstrate that 73% of this study area has a higher value of r_o (-158.4). This implies that change of temperature as simulated from the near future climate change scenarios will most likely affect r_o and therefore population of the leafminer.

As shown in Figure 7, the projected distribution of the normalized r_o of leafminer in the near future climate change scenarios during 2041 to 2070 over Limpopo points to a high rate of multiplication in each generation of the leafminer and this corresponds to optimal temperatures favorable to population growth of pests. Figure 7 shows that the high proportion of this study has a high value of r_o =-155.5 and the lowest proportion of this study area has a lowest value of r_o= -193.9. However, the standard deviation (SD) has a value of 8.734 while the statistic mean average has the value of -167.388. This implies that change of temperature as simulated from the near future climate change scenarios will most likely affect $r_{o.}$

Figure 8 depicts maximum/minimum values of r_o over the northern/southern region of Limpopo province suggesting spatial variability of r_o during the distance future climatic period. In particular, 24% of this study are corresponds to the r_o minima based on the median threshold. This implies that future variability of temperature as simulated from the distant future climate change scenarios will most likely have an effect on r_o. Consequently, the distance future climate period could result in an increase in the pest population over most parts of Limpopo province.

Mean generation time of leafminer under present, near- and distant future climate change scenarios

The effect of temperature under the present climate change scenarios was highly significant for the mean generation time (tg) parameter (F=35.829; R^2=0.9227; pvalue=0.009). Figure 9 illustrates the effect of temperature on the tg between two successive generations of leafminer under the current climate change scenario. Figure 10 represent the spatial variability of the mean generation time (tg) of leafminer in the near projected future climate change scenarios (2041-2070).

From the present analysis, Figure 10 show the near future climatic period which is the range of tg over Limpopo province was determined to be ~3.93. Overall, 29% of the study area exhibited tg values higher than the median value implying that temperature variability of the

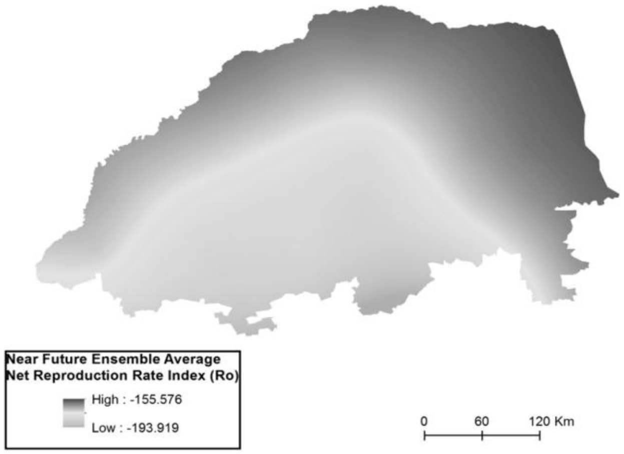

Figure 7. Net reproduction rate (ro) of leafminer under near future climate change scenarios (2041-2070).

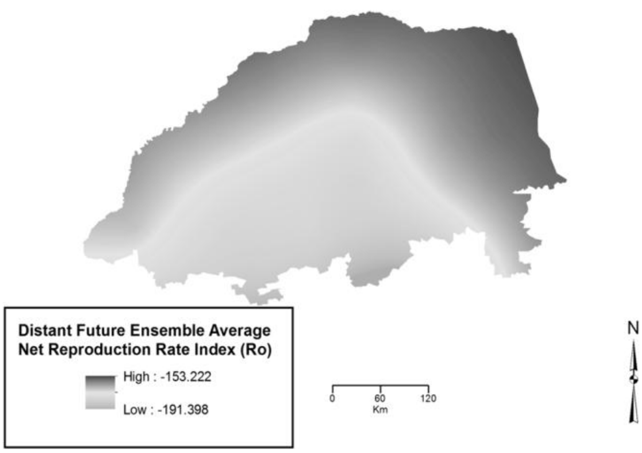

Figure 8. Net reproduction rate (ro) of leafminer under distant future climate change scenarios (2071-2100).

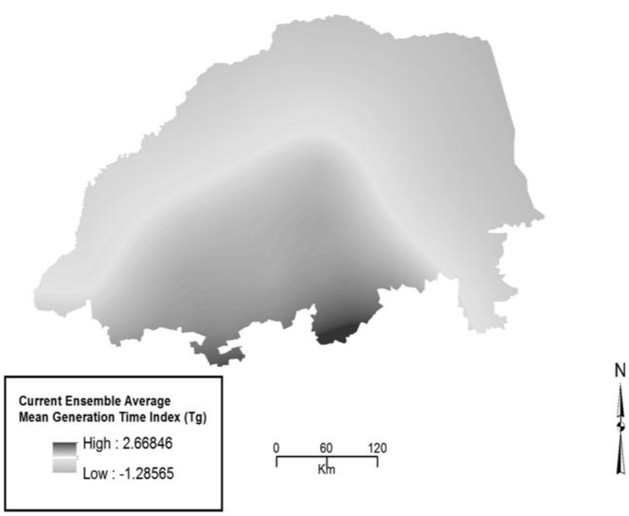

Figure 9. Mean generation time (tg) of leafminer under present climate change scenarios (1981-2010).

near future climate change scenarios will not likely affect tg.

Figure 11 represent the spatial variability of the mean generation time (tg) of leafminer in the distant projected future climate change scenarios. From Figure 11, this study site exhibits a tg mean value ~0.8. Overall, 84% of this study area corresponds to have values lower than the median tg. This implies that future variability of temperature as simulated from the distant future climate change scenarios will most likely not have a noticeable effect on tg. Furthermore, the spatial distribution of tg during distant future suggest a north-south gradient.

DISCUSSION

Several studies have shown that the development and survival of leafminer are significantly affected by temperatures (Wu, 1997). Our results allude to the fact that certain population parameters of leafminer agromyzid were influenced by changes in temperature under different climatic periods. Based on the CCAM simulations of the current climatic period a large proportion of this study area exhibits higher values of r_m suggesting that the temperature variability during will most likely affect r_m. The r_m values under the current and near future climatic periods were however inversely related. Additionally, a large proportion of this study area exhibited values of r_m higher than median during the climatic period of the near future implying that temperature variability of the near future climate will not likely affect r_m. Similar observation was also found for distant future climatic period.

About 73% of this study corresponds to the maxima of r_o based on the median threshold value implying that temperature variability of the current climate change scenarios will most likely affect ro. The current t_g has a higher value of t_g implying that temperature variability in the current climate change scenarios will most likely affect t_g.

The distribution of leafminer agromyzid across Limpopo province appears to be influenced by temperature variability across different climatic conditions. Although insects do not live in a stable environment without temperature fluctuation, the results of studies under constant temperatures are still very useful in understanding the population dynamics of various insect (Summers et al., 1984).

This study contributes towards an understanding of the effects of a broad range of temperature variability on the demography of leafminer agromyzid on tomato crops over Limpopo province, which has not been previously studied. Our results demonstrate that different population parameters (r_m, r_o and t_g) are subtly affected by temperature variability over the different climatic periods as simulated by CCAM. A summary of statistics describing the relationship between temperature and population parameters (r_o, r_m and tg) of leafminer agromyzid are

Table 3. Empirical relationship between temperature (T) and population parameters based on the laboratory experiment depicted in Table 1.

Population parameter	Empirical function based on the range 15.0 ≤ T ≤ 35.0;	Range of the most significant coefficients
Intrinsic rate of increase, (r_m)	r_m=A+BT+CT^2	2.0 ≤ B ≤ 5.0; -0.08 ≤ C ≤ -0.02
Mean generation time, (t_g)	t_g = A+BT+CT^2	10.0 ≤ B ≤ 40.0; -6.0 ≤ C ≤ -3.0;
Net reproduction rate, (r_0)	r_0 = A+BT+CT^2	140 ≤ B ≤ 200; -26.0 ≤ C ≤ -24.0

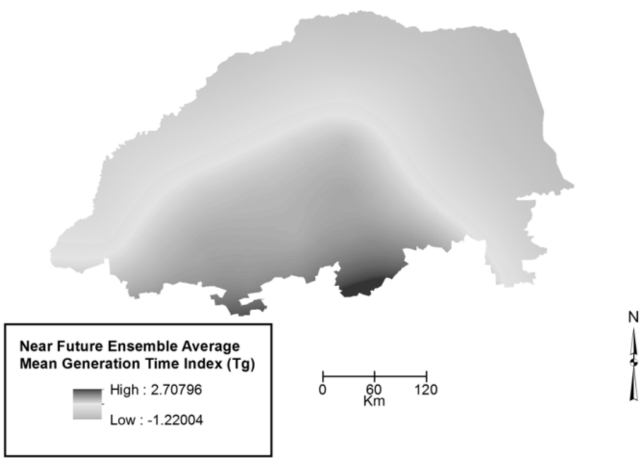

Figure 10. Mean generation time (tg) of leafminer under near future climate change scenarios (2041-2070).

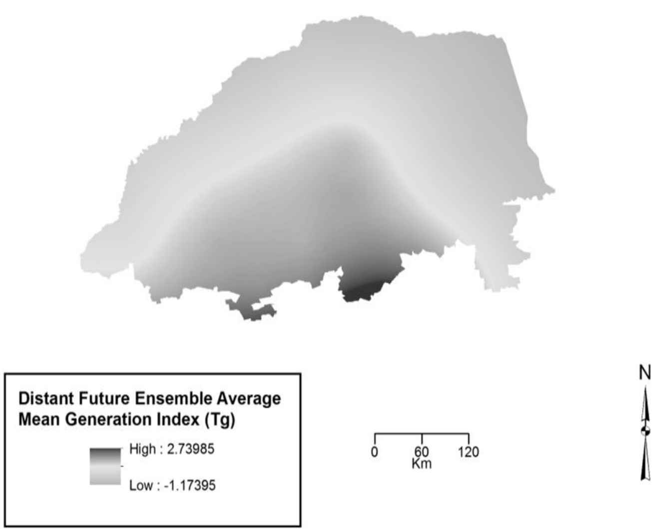

Figure 11. Mean generation time (tg) of leafminer according to distant future climate change scenarios (2071-2100).

presented in Table 3. As shown in Table 3, under the current climate change scenario (1981 to 2010) the high proportion of this study is dominated by the t_g while in the near future scenario (2041 to 2070) the high proportion of this study area is covered by the r_o. In addition, the distant future scenario (2071 to 2100) has high proportion of the study area is dominated by t_g. In general, the impact of temperature on the distribution was not unexpected. This is because in the Northern Province the tomato crop producers are using irrigation system throughout the year and tomato crop is the host of leafminer. The analysis shows that r_m, r_o and t_g parameters respond differently to the different scenarios of CCAM simulations. In this regard, our results corroborate prior work on the climatic effects on the population parameters of pests published in the literature (Walther et al., 2002; Parmesan, 2007; Merrill et al., 2008).

Overall, this present study examined the effect of temperature on the distribution of leafminer pests over a regional extent. It is important to elucidate that a number of biotic and abiotic factors that directly or indirectly influence leafminer pest distribution also come into play. Factors such as precipitation, vegetation cover, soil moisture, competitor organisms etc ought to be included in the predator-prey metric. This metric is vital for the thorough understanding of the fundamental ecological processes that affect the spatial distribution of leafminer pests. Thorough understanding of these factors could contribute towards the development of a robust integrated pest management system of the leafminer pests under the changing climate.

Conclusion

Based on the findings of this present study, the following inferences emerge; (a) the view that climate conditions are the primary factor controlling the distribution of insect pests' populations is supported, (b) temperature will certainly affect the growth and the development of the leafminer agromyzid, as discussed by Leibee (1984). This study considered that the ideal condition for growth of the leafminer agromyzid is at constant temperature 25°C, while the development rates increase with temperature up to about 30°C, however temperatures above 30°C are usually unfavorable and larvae experience high mortality (c). The population parameters of leafminer agromyzid are sensitive to climatic change and trends across Limpopo province implying that the pest population could be affected by continued global warming. It should be noted that all parameters in this present study were estimated at temperatures under laboratory conditions and that factors such as host plants and population density have not been taken into consideration yet they have an effect on the leafminer development and fecundity (Petitt and Wietlishach, 1994). In conclusion, our current assessment of the impact of temperature as simulated by CCAM for different climatic periods on the distribution of leafminer agromyzid pest introduces new questions that is, (a) how do the combined biotic and abiotic conditions influence leafminer agromyzid pest distribution over Limpopo? (b) Do different General Circulation Models (GCMs) reproduce the observed influence? (c) How optimal are the derived empirical functions that link climatic factors to the population parameters of leafminer agromyzid pest? In conclusion, we remark that more attention should be devoted to semi-field experiment to obtain more applicable results under field conditions.

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