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Response of a rice insect pest, *Scirpophaga incertulas* (Lepidoptera: Pyralidae) in warmer world

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Abstract

Background: Increases in global mean temperature, changes in rainfall patterns, and extreme climatic events are expected results of climate change. The individual effects of elevated temperature and precipitation on insect pests due to the impact of climate change have been widely modeled individually but their combined effects are poorly understood.

Results: Ten years of monthly abundance of an important economic rice insect pest, the rice yellow stem borer (YSB), *Scirpophaga incertulas* Walker (Lepidoptera: Pyralidae), was modeled in relation to temperature and rainfall using cross-correlation functions, general linear models, ARIMA models and simple linear regressions. The results suggested that increasing temperature and rainfall separately had a positive effect on growth rate of YSB. However, the combined effect of high temperature and rainfall was negative Temperature affected abundance of YSB negatively at high rainfall, but positively at intermediate to low rainfall level. The growth rate of YSB was found to be high at relatively low temperature and abundant rainfall.

Conclusion: The combined effects of temperature and rainfall showed a quadratic response of YSB abundance, which indicated that outbreak risk of YSB may be reduced if climate change results in increasing temperature and rainfall. It should be noted that we could address only a few of the important factors which could influence our model prediction.

Background

Global temperatures are projected to increase 1.4 to 5.8 °C by 2100 in conjunction with precipitation increases of 10 to 15% and higher rates of occurrence of heat waves and cold snaps [19]. These changes will have major influences on the abundance, distribution and ecology of plants and animals worldwide [2, 9, 21, 22, 30–33].

Both temperature and precipitation strongly affect insect development. Not only do they directly regulate growth but they also regulate host selection and conspecific or predator / prey interactions [3, 6, 11, 12, 16, 17, 21, 22, 24, 26, 39, 40]. For example, temperature affected feeding competition between burying beetles *Nicrophorus orbicollis* Say and *N. defodiens* Mannerheim (Coleoptera: Silphidae), as well as intraspecific competition of *Camnula pellucida* (Scudder) (Orthoptera: Acrididae) grasshoppers [25].

Rice is the main food staple for more than half of total human population. More than 100 insect pest species eat rice. Among them 20 species are major pests and cause great economic damage. The rice yellow stem borer (YSB), *Scirpophaga incertulas* Walker (Lepidoptera: Pyralidae) is considered as the most economically important insect pest of rice, and is found in all rice growing countries, particularly in Asia. During the rice growing season, YSB attacks the rice plant at its vegetative stage causing a characteristic visible

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symptom in rice fields called dead-heart (Fig. 1a). Later, at the reproductive stage, it produces white-head symptoms (Fig. 1b). This pest can cause large (3 to 95%) grain yield losses [15]. Each of the YSB life stages are significantly influenced by temperature [28]. Several factors including biotic, abiotic (climatic), crop variety, pest management and cultural practices affect the incidence and abundance of YSB in rice field. Among the climatic factors, temperature is considered to have the greatest influence on YSB abundance in the field. Climate change is expected to affect the behavior as well as distribution and abundance of YSB in southern Asia by increasing winter survival rates and the number of generations per year, as well as inducing an earlier appearance in the crops after winter [37]. In addition, the physiological impacts of climate change on rice development is expected to reduce rice yields more than 30% over the next 80 years [27].

Rising temperature is known to be a leading cause of insect outbreaks in boreal forests [42]. However, the abundance of *S. incertulas* has decreased over the last three decades [14, 45], possibly due to mortality caused by higher temperatures and rainfall during July compared to previous decades [1, 8]. Our model of YSB abundance presented here, derived from analyses of the previous effects of temperature and rainfall on YSB abundance over time, suggests that global warming may cause even lower abundance of YSB during July in future decades. To develop the model, we used simultaneous data of atmospheric temperatures, rainfall and YSB daily light trap captures collected over a ten-year period, to understand potential relationships between climatic variables and YSB abundance.

Results

To consider recent effects of global warming and increased rainfall on abundance of *S. incertulas* in Bangladesh, we conducted an experiment between 2006 and 2015 to obtain long-term abundance and weather data (please see details in Materials and method section). A light trap was used to collect *S. incertulas* adults. Because light trap catches can be different from real field numbers, we also sampled weekly for immature stages. Comparisons between light trap captures and field samples indicated that only 6.0% of the population remains in the field, and 94% of the population ultimately is caught in the light trap, confirming that the light trap catches are an effective tool to monitor YSB in rice fields. Consequently, we used the light trap catches as monthly estimates of YSB abundance.

The monthly abundance of *S. incertulas* displayed seasonality (Fig. 2a-b). The results also showed that abundance was highest between April and June and also from August to November (Fig. 2a-b). December to March had the lowest abundance of the yearly seasons. In Bangladesh, there are three rice production seasons, monsoon rice, “Aus” (March–August), rainfed and supplement irrigated rice, “Transplanted Aman-T. Aman” (June–November) and irrigated and winter rice, “Boro” (December–March). A time series analysis and periodogram of monthly log abundance of *S. incertulas* confirmed the seasonality of abundance and showed the strongest periodicity at 6 months, followed by a weaker periodicity of 12 months (Fig. 2c).

Cross-correlation analysis showed a potential association of *S. incertulas* abundance with temperature and rainfall (supplementary information, Table S1). The highest cross correlation function (CCF) values of abundance of *S. incertulas* with temperature and rainfall were 0.556 and − 0.402 respectively. It indicated that the associations of abundance of *S. incertulas* with temperature and rainfall might be positive and negative, respectively. However, further analyses showed that the relationships of abundance of *S.*

Fig. 1 Damaged symptom of rice at field due to yellow stem borer, *Scirpophaga incertulas* (Lepidoptera: Pyralidae) infestation. **a** Shows the dead heart symptom observed at vegetative stage. **b** Shows the white head symptom observed at reproductive stage

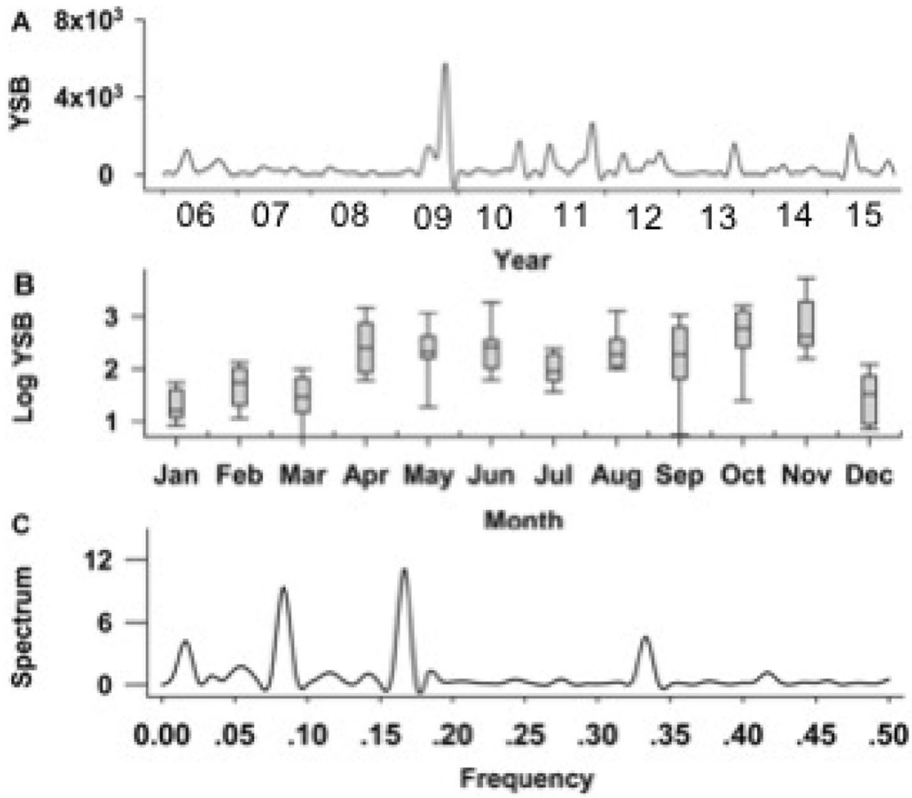

Fig. 2 Monthly abundance (**a**), variation (**b**) and estimated periodogram (**c**) of *Scirpophaga incertulas* Walker in Bangladesh during January 2006–December 2015

incertulas with temperature and rainfall might be more complex than initially expected.

We found that the monthly abundance of *S. incertulas* varied on its own previous demographic history as well as temperature and rainfall ($Y_t = 0.458\ Y_{t-1} - 0.518\ Y_{t-2} + 0.306\ Y_{t-3} + 0.002\ T^{2}_{t-1} - 1.553R^2_t - 0.225T_t\ R_t + 7.462R_t$; $R^2 = 0.652$, AIC = 1.153). We also found that the residual from this regression model could be successfully modeled as per Hulme and Viner [18] by using a subset ARIMA (12, 0, 2) (1, 0, 1) model (Supplementary information, Table S2). Variance partitioning results showed that combination of temperature and rainfall explained a total of 30.2% of the variance in abundance of *S. incertulas*, while temperature and rainfall explained 22.7 and 7.5% each, respectively (Fig. 3). The results indicated that the individual effect of temperature and rainfall and their combined or interaction effect were significant (Table S2). However, temperature explained more of the variance in abundance of *S. incertulas* than the rainfall.

Results of simple linear regressions supported a hypothesis that climatic factors (e.g. temperature and rainfall) had a quadratic effect on *S. incertulas* population dynamics (Fig. 4). At high rainfall level temperature affected abundance of *S. incertulas* negatively, but the effect was positive at intermediate to low rainfall levels (Fig. 4a). Rainfall affected the abundance of *S. incertulas* positively in two situations, when monthly rainfall was less than 400 mm at high temperature and when monthly rainfall was less than 300 mm at intermediate temperature. On the contrary, the impact of rainfall on the abundance of *S. incertulas* was negative when monthly rainfall was more than 400 mm at high temperature, and when monthly rainfall was more than 300 mm at intermediate temperature (Fig. 4b).

For more evidence that elevated temperature and rainfall reduced the abundances of *S. incertulas*, we measured the response of growth rate (r) of *S. incertulas* to climate variability (factors) using a general linear model, $r = ß_0 + ß_1T + ß_2T^2 + ß_3R + ß_4R^2 + ß_5TR + ß_6T^2R + ß_7TR^2 + ß_8T^2R^2 + \varepsilon$.

The model was selected based on the lowest AIC value. The best fitted model for *S. incertulas* ($F_{4,\ 113} = 5.70$; $P = 0.0003$) growth rate, was $r = -0.05516(0.02401) + 0.00429(0.00111)T + 0.00000468(0.00000141)R^2 - 0.0000001861(0.00000005)TR^2 - 0.0067314162(0.00353037)\ \ln N$.

Values of standard errors of the estimated parameters are shown in parentheses. At high temperature and rainfall, the model indicated that increasing temperature and rainfall influenced positively on growth rate but an interaction effect of temperature and rainfall had negative

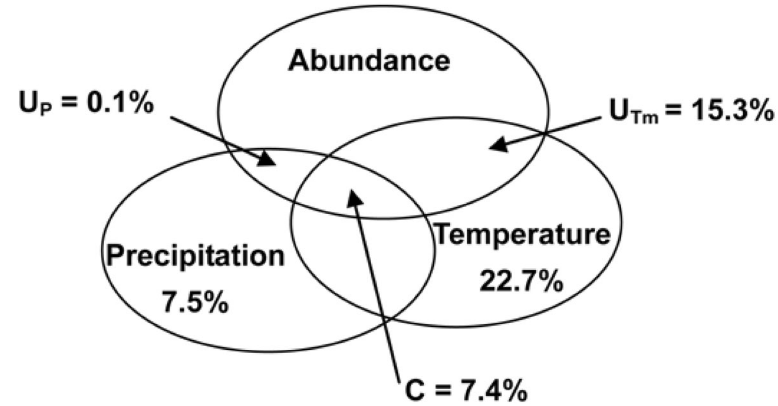

Fig. 3 Partitioning the variance of monthly abundance of *Scirpophaga incertulas* accounted for by climate parameters in Bangladesh. Monthly abundance of *Scirpophaga incertulas* was log (x + 1) transformed before this analysis. Rainfall and temperature refer to monthly rainfall and the average of monthly maximum and minimum temperature. U_{Tm} and U_P mean the unique effects accounted for by temperature and rainfall respectively; C means the joint effect accounted for by both temperature and rainfall

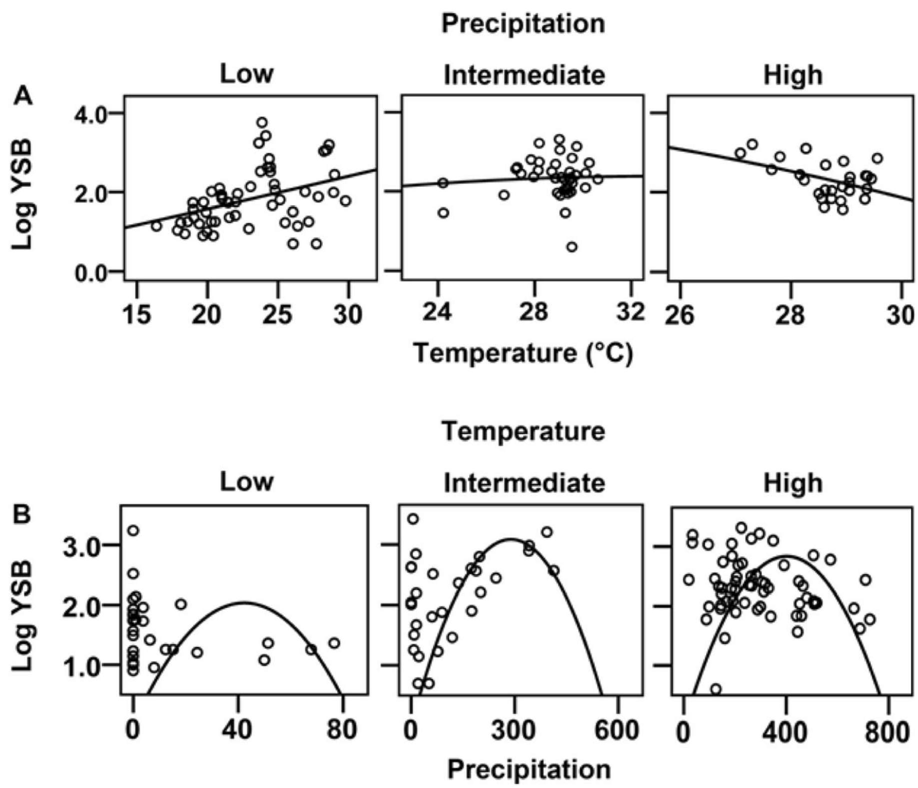

Fig. 4 Quadratic interactions of monthly precipitation (**a**) and temperature (**b**) on rice stem borer in Bangladesh. The response variable monthly abundance of *Scirpophaga incertulas* was log (x + 1) transformed before analysis. For the simple linear regressions between abundance and temperature at high, intermediate and low rainfall (**a**), $R^2 = 0.971$, 0.956 and 0.887, respectively; $F = 419.783$, 389.432 and 203.806, respectively; sig. < 0.001, 0.001 and 0.001, respectively. For the simple linear regressions between abundance and precipitation at high, intermediate and low temperature, $R^2 = 0.871$, 0.644, and 0.188, respectively; $F = 191.949$, 24.374 and 3.367, respectively; sig. = < 0.001, 0.001 and 0.050, respectively. See the text for detail

influence ($F_{4,\ 113} = 5.70$; $P = 0.0003$). The relationship among growth rate, temperature and rainfall showed that the per capita growth rate was higher at relatively low temperatures and elevated rainfall and lower at high temperature and elevated rainfall (Fig. 5). However, abundance of YSB would be higher when temperature prevail 10 to 25 °C with an amount of rainfall 400 to 700 mm. At higher temperature and rainfall, the forecasted growth rate also supported a result that the outbreak risk of *S. incertulas* might decrease. Note, however, that the model of predicted growth rate has not been validated for extreme combinations of temperature and rainfall.

The expected population size at time $t + \Delta t$ can be obtained from $E(N_{t+\Delta t}) = N_t\ e^{r\Delta t}$. The model's ability to predict the population size at time $t + \Delta t$ depends on temperature and rainfall during the time interval. We can therefore only predict the future population size if we have knowledge of how the weather will be during the period. One guess could be to use the average values for the period in focus. However, if we use the model retrospectively, we can replace temperature and rainfall with the actual values and use N_t instead of N to estimate the expected growth rate during the period and then insert it into the equation to forecast $E(N_{t+\Delta t})$ from knowledge of N_t.

Discussion

Now it is very important to investigate the impact of climate variables on the structure and diversity of the insect community [44], as insects could play important roles in ecosystem functioning [5, 29]. This study is more likely subjected to gain the knowledge of results on swift ongoing climate change on the ecosystem and species. Global warming is responsible for vertebrate, invertebrate, and plant range shifts [36, 43]. Comparatively fewer research findings have been documented describing the possible impacts of climatic variables such as precipitation and temperature on the relationships within biotic communities [10, 35], but given the strong dependence of many organisms on particular climatic signals and precipitation levels, it is likely that such effects have been addressed in the present paper.

In this study, we used 10-year monthly abundance of an important rice insect pest *S. incertulas* and their response to temperature and rainfall was analyzed. Our results indicated that both temperature and rainfall have prediction power of the abundance of YSB. Both their individual and combined or interaction effect were significant (Table S2). This result was consistent with prior studies which showed that the fluctuation of *S. incertulas* abundance was regulated mainly by abiotic factors [4, 41] and indicated that the response of *S. incertulas* to climate variability might be quadratic, due to potential interactions between temperature and rainfall. However, temperature explained more of the variance in abundance of *S. incertulas* than the rainfall. Rising temperature, decreasing rainfall, and intensifying agricultural production induce outbreak of *H. armigera* [34]. Our results also showed that rising temperature induce higher abundances of YSB in rice field at lower rainfall condition. However, if both temperature and rainfall increased simultaneously, the incidence of YSB would be declined (Fig. 5). Climate change and agricultural intensification could potentially induce the outbreaks of pest insects through weakening the density-dependent population regulation [34]. Though

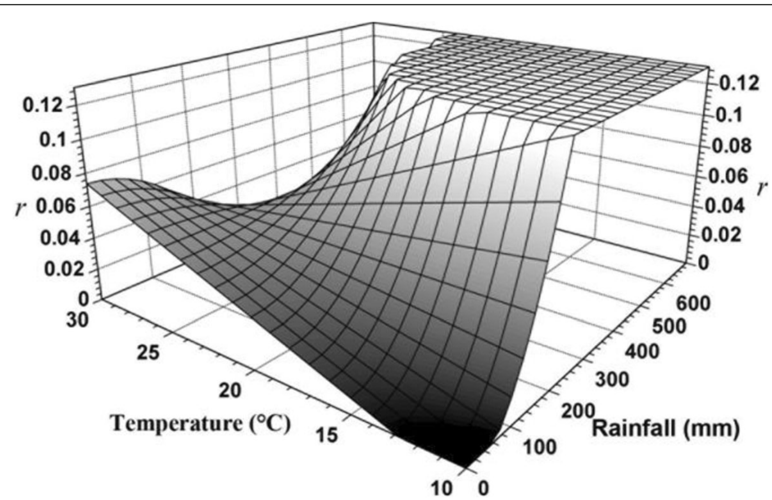

Fig. 5 Predicted per capita growth rate (*r*) for *Scirpophaga incertulas* at different combinations of temperature and rainfall. As the maximum empirical value of *r* was found to be 0.13 day^{-1}, the vertical axis is truncated at this value

we did not include the agricultural intensification as a factor to explain our results we can consider that agricultural intensification has profound impact on insect pest outbreak in any field.

Results suggested that climatic factors (both elevated temperature and precipitation) might not cause an increase in the frequency of *S. incertulas* outbreaks in rice fields. Instead, the frequency of outbreak of *S. incertulas* might be reduced. Similarly, Karuppaiah and Sujayanad [20] had reported that higher temperature influenced the population dynamics of other rice insect pests for example, brown plant hopper *Nilaparvata lugens* (Stal) and rice leaffolder, *Cnaphalocrocis medinalis* (Guen), by lowering the survival rate. However, rainfall shows both positive and negative relationship with insect pest abundance. Bhowmik and Saha [7] found that rainfall had non-significant negative correlation with the abundance of red pumpkin beetle. Ghule et al. [13] reported that rainfall positively influenced the population of fruit fly infesting ridge gourd. Maximum temperature had negative correlation whereas evening relative humidity had positive correlation with fruit flies infestation [38].

Based on our statistical model, we concluded that global warming might be responsible for the recent declining trend of *S. incertulas* in rice field. Similar declining trend in abundance of *Plutella xylostella* has been reported due to global warming by Kiritani [23]. However, he also reported an increasing trend in abundance of *Helicoverpa armigera* and *Trichoplusia ni* due to the global warming [23]. Elevated temperature influenced each growth stage of insect pest and thus regulated the abundance and distribution by impacting the growth, reproduction and development [20].

Increases in global mean temperature, changes in rainfall patterns, and extreme climatic events are expected results of climate change [19]. From the statistical results of this study, we have modeled how recent levels of global warming have affected abundances of *S. incertulas*. As temperature and rainfall increase due to climate change, *S. incertulas* outbreaks may decrease. A quadratic response pattern also suggested that, as climate change affects abundance of *S. incertulas*, its effects may be of importance also for other pests. The abundance of *S. incertulas* showed a declining trend over the last three decades both in Bangladesh and Pakistan [14, 45], which would be of benefit to their rice farmers who improve their pest management practices, since this is their key pest of rice and rice is the main staple food for more than half of global human population.

The present study of the abundance pattern of *S. incertulas* is provided here to explain associations between outbreaks of a major rice pest and climate change. However, it is not easy to draw specific predictions as to how climate change occurs and how the changes affect specific herbivore–associations. Incorporation of long-term demographic-herbivore data and the effects climate change on the associated hosts, as well as more geographically detailed models of local climate changes could improve the predictions of these models in explaining the responses of insect pests to climate change.

It should be noted that we could address only a few of the important factors which could influence our model prediction. Though our analysis showed that joint effect of elevated temperature and rainfall had a negative effect on the abundance of *S. incertulas* in rice field, we had not included other factors, e.g., crop stage and pest management practices that might also have important effects on abundance patterns. Moreover, we have used light trap data from a single location e.g. the BRRI Farm. Therefore, data from different geographic locations could provide more realistic predictions for specific field sites. More importantly, the declining trend of abundance of *S. incertulas* in South Asian countries especially in Bangladesh and Pakistan [14, 45] could also be attributed to successful pest management activities such as IPM, cultural practices, and insecticide applications.

Methods

Data collection

The YSB in this study were monitored daily using a light trap (Pennsylvania type, BRRI, Gazipur) placed in 20 Ha of rice fields at Bangladesh Rice Research Institute (24°0`0``N, 90°25`48``E). Light trap catches of YSB were daily collected, identified and preserved at the Entomology Division of BRRI. The time series of monthly YSB catches from January 2006 through December 2015 were then calculated and used in this study. A field survey was conducted at each week during this period as an alternative method to monitor YSB abundance. One hundred complete sweeps were taken to record adult YSB from BRRI research farm. In addition, 20 rice hills were examined to record immatures at the same at each week. All the climatic data (e.g. temperature, rainfall etc) used in the study were obtained from the Plant Physiology Division of BRRI (www.brri.gov.bd). These data covered the same study period and the area.

Data analysis

Light trap catch data were compared with the field survey data and the abundance proportion was calculated. Monthly abundance of *S. incertulas*, *N*, was $\log_{10}(x+1)$ transformed to improve the additivity and normalize the distribution of the time series data. The resulting series was used as the response variable (Y). Monthly maximum (T_{max}°C)-, minimum (T_{min}°C) temperature and $\log(x+1)$ transformed rainfall (R, mm) were used as the explanatory variables. As the highest value of cross-correlation function (CCF) of *S. incertulas* abundance with T ($T = (T_{max} + T_{min})/2$) is higher than those with T_{max} and T_{min} (Table S1), we used T as a dummy proxy of T_{max} and T_{min} in subsequent analyses.

To determine the periodicity of *S. incertulas* population dynamics, spectral and CCF analyses were conducted to determine potential associations between the transformed response, Y, and explanatory variables, T and R. An augmented Dickey-Fuller unit root test showed that response variable was stationary. Therefore, there was no need to differentiate it in the following analyses. The Akaike information criterion (AIC) was minimized by first selecting autoregressive (AR) and moving average (MA) orders and then removing non-significant AR and MA parameters (Bozdogan 1987 for AIC, and ARIMA). The AIC then was used for optimal correlation structure of the autoregressive integrated moving average (ARIMA) model. The Lagrange Multiplier Test and Augmented Dickey-Fuller Unit Root Test were used for proper autocorrelation and non-stationarity, respectively in the residual series of models of the study. A subset ARIMA (12, 0, 2) $(1, 0, 1)^{12}$ model was used for adjusting for serial residual correlation and the model, $Y_t = 0.458\ Y_{t-1} - 0.518\ Y_{t-2} + 0.306\ Y_{t-3} + 0.002T^2t\text{-}1\ -1.553R^2t\ -\ 0.225T_t\ R_t + 7.462R_t$; $R^2 = 0.652$, AIC = 1.153). The Autoregressive (AR) parameter for lag12, seasonal autoregressive (SAR) parameter for lag 1, moving average (MA) parameter for lag 2, and seasonal moving average (SMA) parameter for lag 1 were included in the subset ARIMA model (Table S2), with the other AR and MA parameters coefficients set to zero.

To reveal potential interactions between temperature and rainfall, we divided temperature and rainfall into three levels (temperature: high $T_m > 28\,°C$, intermediate $28\,°C > T_m > 24\,°C$ and low $T_m < 24\,°C$; rainfall: high $P > 300$ mm, intermediate 300 mm $> P > 100$ mm and low $P < 100$ mm), and then conducted simple linear regression analyses by using a quadratic model without constant in the regression equations. As rainfall and temperature were correlated (the highest CCF value between these two series was 0.620 at lag 0), we conducted regression commonality analysis to partition the variance accounted by each of the explanatory variables.

The average per capita [Is this a commonly used term for insect abundance? Per capita normally means per person] growth rate *(r)* was calculated from time *t* to time $t + \Delta t$, where *N* is denoted as the population size. Here, monthly abundance of *S. incertulas* and $N = (N_t + N_{t+\Delta t})/2$ i.e. the average population size from time *t* to time $t + \Delta t$. *T* and *R* are denoted as the average temperature and amount of rainfall during the time interval, respectively. By means of a general linear model, we investigated whether *r* depends on temperature and rainfall and the model as below -

$$r = ß_0 + ß_1 T + ß_2 T^2 + ß_3 R + ß_4 R^2 + ß_5 TR + ß_6 T^2 R + ß_7 TR^2 + ß_8 T^2 R^2 + \varepsilon$$

We used PROC REG in SAS (2007) to estimate the parameters of the model using a backward elimination method with $p > 0.1$ as a criterion for dropping terms from the model. To account for a density-dependent effect of population size we added an extra term. The extra term was either $ß_9\ N$ or $ß_9 \ln N$. The temperature that best predicted *r* was the daily minimum.

Supplementary information

Supplementary information accompanies this paper at https://doi.org/10.1186/s40850-020-00055-5.

Additional file 1: Table S1. Values of cross-correlation function between monthly abundance of *Scirpophaga incertulas* Walker and climate parametric in Bangladesh. T_{max} and T_{min} mean monthly maximum and minimum temperature (°C). T is equal to $(T_{max} + T_{min})/2$. H means monthly precipitation/rainfall. Monthly abundance of *S. incertulas* was log $(x + 1)$ transformed before analysis. Numbers in bold indicate that the coefficients were significant (2-tailed): $P < 0.05$.

Additional file 2: Table S2. Summary information on the regressive model for the monthly abundance of *Scirpophaga incertulas* Walker in Bangladesh during 2000–2009. Y and H mean log (x + 1) transformed monthly abundance of *S. incertulas* and monthly precipitation. T means the average of monthly maximum and minimum temperature. The serial residual correlation was adjusted using a subset of seasonal autoregressive (AR) integrated moving average (MA) model, ARIMA $(12,0,2)(1,0,1)^{12}$.

Abbreviations

AIC: Akaike information criterion; AR: Autoregressive; CCF: Cross correlation function; GLM: Generalized linear model; IPCC: Intergovernmental panel on climate change; MA: Moving average; ARIMA: Autoregressive integrated moving average; SAR: Seasonal autoregressive; SMA: Seasonal moving average; YSB: Yellow stem borer; T_{max}: Maximum temperature; T_{min}: Minimum temperature

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Authors' contributions

Research designed by NA, SSH, MNB and MPA; MMMK, MPA and NA collected data; MPA analyzed data and wrote the paper; RM, FN, TRC, SSH, MNB and NA edited the paper. All authors have read and approved the manuscript.

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Availability of data and materials

Data information is accessible by providing in supplementary files. All other information require to understand the manuscript can send request to corresponding author for sharing the data.

Ethics approval and consent to participate
Research did not involve any human participants, human material, or human data.

Consent for publication
Not applicable for this research.

Competing interests
The authors declare no conflict of interest.

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