Frontiers in Sustainable Food Systems

TYPE Opinion
PUBLISHED 28 May 2024
DOI 10.3389/fsufs.2024.1361012

OPEN ACCESS

EDITED BY
Subramanian K. S.,
Tamil Nadu Agricultural University, India

REVIEWED BY
Gemma Clemente-Orta,
Universitat de Lleida, Spain
Soumi Mitra,
Baylor College of Medicine, United States

*CORRESPONDENCE
Arup Kumar Sarma
arup.sarma@aau.ac.in

RECEIVED 24 December 2023
ACCEPTED 07 May 2024
PUBLISHED 28 May 2024

CITATION
Sarma AK, Damgaard CF, Saikia M and Neog P (2024) Rapid assessment and management of outbreak of Rice Swarming Caterpillar by drone: a BIG need of the hour.
Front. Sustain. Food Syst. 8:1361012.
doi: 10.3389/fsufs.2024.1361012

Rapid assessment and management of outbreak of Rice Swarming Caterpillar by drone: a BIG need of the hour

Arup Kumar Sarma[1]*, Christian F. Damgaard[2], Mrinal Saikia[3] and Prasanta Neog[4]

[1]AAU-ZRS, Assam Agricultural University, Nagaon, India, [2]Department of Ecoscience, Aarhus University, Aarhus, Denmark, [3]Directorate of Research (Agri.), Assam Agricultural University, Jorhat, India, [4]BN College of Agriculture, Assam Agricultural University, Biswanath Charali, India

KEYWORDS

***Spodoptera mauritia*, drone, resilience, epidemic, pest, synchrony, insectivorous bird, Assam**

Introduction

Rice is grown in more than 100 countries and is used as a staple food by more than half of the world's population (Fukagawa and Ziska, 2019) including 560 million poor people (GRiSP, 2013). Thus, any event that causes major reduction in rice yield may bring a threat to food security of such a large population that it may result global social crisis. Outbreak is an event where a population of a species grows manifold within a short period. Outbreaks of insect pests have plagued the planet from time immemorial (Berryman, 2008). In the Indian context, outbreaks of Rice Swarming Caterpillar (RSC) have become a threat to rice cultivation in many states (Tanwar et al., 2010; Sarma et al., 2013; Upamanya et al., 2013; NRRI, 2016; Baruah, 2017; Jena et al., 2017; Sampathkumar et al., 2018; Sarma and Gupta, 2018; Sarma and Salam, 2018; Amala et al., 2019).

The issue of outbreak of RSC has emerged as a major threat to rice cultivation, because of its increased frequency of occurrence and exclusive dependence on chemical insecticides used for its combating. As compared to just 10 times in the past century the outbreaks occurred 9 times in the past 2 decades (2001–2020) in India (Sarma et al., 2021) excluding the local RSC outbreaks many of which remained unreported in scientific journal (Sarma et al., 2023a,b). To combat the RSC outbreak in 2016 in Assam, about 25,545–42,576 L insecticide was applied in more than 56,768 ha of winter rice in Assam, an Indian state known for its organic cultivation (Sarma et al., 2021). The chemical insecticides were used in a *no way-out situation* because an outbreak is a disaster that cannot be allowed to continue. However, it is a matter of concern that such a massive addition of insecticides may pose a threat to the resilience of the rice ecosystem (Sarma et al., 2021). Credible predictions will help in the early adoption of non-chemical preventive measures as well as to avoid injudicious chemical application (Sarma et al., 2023a,b). The RSC outbreak is truly an agricultural crisis, but it turns out also to be a socio-political issue if it continues for weeks together. Farmers want a quick solution of the outbreak, and people criticize the Government and other stakeholders seeking quicker eradication of it. Early outbreak detection and treatment application are inherent to effective pest management, allowing management decisions to be implemented before pests are well-established and crop losses accrue (Filho et al., 2019). Here lies the need for the modern agri-engineering gadgets which can quicken the survey, detection of infestation and management of the outbreak. Moreover, as labor availability and technical manpower are extremely limited, particularly in India, drones are gaining popularity in the context of smart farming (Subramanian et al., 2021). An attempt has been made here to highlight the event of outbreak and possible uses of drones during RSC outbreak so that researchers may further investigate, and policy makers can adopt possible recommendations.

The opinions stated here are synthesized primarily from the published literatures on the outbreaks of RSC occurred in Assam, India and the pertinent literatures published from other places. The said literatures have been mentioned in the suitable section below.

Discussion

The outbreak of a pest species in a crop ecosystem warrants an emergency management; because, during outbreak, the pest appears and spreads within a short period in abnormally large numbers in a large area, manifold to its normal population of non-outbreak years; e.g., the mean RSC population in rice foliage during normal (non-outbreak) and outbreak years were 0.04 and 36.80 per sqm, respectively (Sarma and Gupta, 2018). In Nepal, remarkably high population of armyworm in rice has also been reported to a tune of 36.0 per sqm during outbreak period (Mainali et al., 2014). Thus, an early detection of RSC outbreak and its rapid assessment of crop damage are essential in order to prevent the abrupt and manifold increase over the EIL. The intensity and area of infestation of the outbreak is determined by the temporal and spatial characteristics of the outbreak. Temporally, the smaller the time-gap between the appearance of voracious late instar larvae and their spread, the more intense is the outbreak. Spatially, the horizontal spread of RSC per unit time from the point of initiation of outbreak is favored by large crop fields situated close to each other. In general, a higher pest load in a crop field is a big determining factor of an outbreak; however, every species with the same pest-load may not result the same extent of damage to a crop, e.g., a pest species with a swarming behavior, such as RSC, has a higher damaging potential than another species without such behavior with the same pest-load. A swarming species may cause an extensive damage. Thus, it is not only the pest-load but also the damage potential of a pest-species per unit time (say, per week) per unit plant (or hill in rice) is another bigger issue.

Swarming is a highly interdisciplinary topic (Bouffanais, 2016). Even though swarming is a physical event, it is triggered by higher fecundity which is an innate physiological character of a species. Thus, swarming is a bio-physical phenomenon favored by many ecological factors, such as phenological stages of the crop, weed species, competitive pest species, natural enemies, inter-plot bunds, flood, soil moisture, air temperature, RH, rainfall etc. If the innate higher physiological fecundity of RSC is not supported by the ecological factors such as favorable weather, food availability, flow of water as dispersing agent, continuity of fields, spacing and size of inter-plots bunds etc., no bio-physical swarming can turn into a massive outbreak. The International Rice Research Institute, Philippines identified four favorable factors for population build-up of RSC (http://www.knowledgebank.irri.org/training/fact-sheets/pest-management/insects/item/armyworms). Prevalence of such favorable biotic and abiotic factors is essential not only to initiate, but also to sustain the outbreak. Thus, the ecological attributes are the main driving force behind an onset and sustenance outbreak and therefore, at least a few of these favorable factors must be synchronized in the crop ecosystem. A better synchronization can make the outbreak happen in large area. *Spodoptera mauritia* (Boisduval, 1833) is a polyphagous species and sometimes move or carried from forest ecosystem to crop. Thus, the "Moran effect" (Moran, 1953) and the "Spatial Synchrony" (Bjørnstad et al., 1999; Liebhold et al., 2004) between its populations in forest and rice ecosystem may have some role in the outbreak of RSC. However, the required synchronization of such environmental factors does not occur each crop season, and therefore, the outbreak does not occur in every season. Thus the extent and period such synchronization determine the onset, intensity and sustenance of an outbreak.

Early detection of occurrence and the horizontal spread of an outbreak is one of the most important inputs for effective management of the outbreak. RSC has year round activity in multi-cropped area (Pathak and Khan, 1994), but because of its diurnal hiding behavior and nocturnal feeding habit (Tanwar et al., 2010), it becomes inconvenient to know its presence and population build up. With the conventional monitoring method, it is not always possible to assess the spread of the outbreak quickly, especially in large paddy fields where the initiation of outbreak remains unnoticed for many days. The most common method deployed for surveying pests in paddy is visual method using quadrant. The initiation of outbreak of RSC in 2016 in Assam remained unnoticed for days together. The information of the outbreak came from farmers after observing the presence of large flocks of insectivorous birds in vertical physical structures like trees, electric transmission line, bird-perches etc. (Sarma et al., 2021). By that time, the pest got enough time for its spread and damage in new areas. Therefore, there is a need of adopting mechanized and prompt surveying tool for quicker monitoring.

Swarm behavior is the collective motion of a large number of self-propelled entities (O'Loan, 1998). The marching of swarming caterpillars is a real time phenomenon. Every additional night in between two incomplete surveys by conventional methods would allow the swarm move forward and damage the crop. However, if drone is used promptly, survey and spraying would be possible in the same day. If the survey is completed in a day, the swarming front would remain in the same place in the paddy field, since the caterpillars usually remain hidden in the base of rice hills in the day time and move forward in swarms at night (Tanwar et al., 2010; Sarma and Gupta, 2018). If compared, the effective area surveyed by drone in one day will be less due to stagnation of swarming-front as compared to moving swarming-front in conventional survey in 2–3 days. Thus, the less effective area surveyed by drone would save the energy and time which may be utilized in spraying insecticide for combating the outbreak.

Drones have multifaceted applications in the field of agriculture. It is now recommended to use in sampling of insects and for spraying of agro-chemicals and use of drones for surveying arthropods has also been carried out in recent years (Carrasco-Escobar et al., 2022; Madden et al., 2022; Ryu et al., 2022; BettiSorbelli et al., 2023; Trujillano et al., 2023). In Japan, drones have been used in agriculture since the 1980s, drones are widely used to spray pesticides on rice crop (Filho et al., 2019). However, no thought has been put forward in the use of drones during RSC outbreak. Drone can be used in surveying rice fields during and even before the initiation of RSC outbreak under a proper prediction system. The survey process would save time and labor as compared to conventional survey which would in turn help dissemination of alert message to farmers, and timely management of pests.

Drones, in the context of outbreak of RSC, may be used in following activities:

To identify the natural RSC hubs

Sarma et al. (2021) emphasized in locating RSC hubs in each agricultural circle of Assam in order to monitor and predict the RSC populations. Sarma et al. (2023a,b) emphasized the application of drone to identify the perennial habitat of rice hispa, rice swarming caterpillars, stem borers, etc. for necessary action at their breeding sites to prevent their outbreak. Drone technology will play a significant role in identifying such hubs and perennial habitats rapidly. On pilot basis, monitoring of such RSC hubs can be initiated in one district, and it may be replicated in other districts later. A district can be divided into grids and the rivers flowing through it may provide probable hubs. Once these hubs are identified, *in situ* preventive measures can be adopted regularly during crop season based on the weather-based prediction.

To know the presence of large of flock of insectivorous birds in and around rice fields

The presence of a large flock of insectivorous birds in and around the rice fields consistently for days together is an indication of presence of large population of RSC which may cause massive outbreak, if not addressed properly. Birds may perch on the trees in and around the paddy field or power transmission line (Sarma and Salam, 2018) in absence of other suitable perching structures in crop fields (Sarma et al., 2021). Many a times, such bird-flocks remain unnoticed in conventional survey due to bigger size of rice field and/or mismatch of between perching time of birds and survey time; however, a drone may be used effectively to locate such flocks in a large field also. A timely tracing of such flocks would alert the farmers for confirmatory field-visit and to take possible preventive measure for combating a possible outbreak. However, disturbances to the flock owing to the drones' movement may be taken in to consideration.

Efficacy of three types of drones have been successfully tested as bird deterrent tool against foraging blackbirds from commercial sunflower fields in North Dakota, USA and came to conclusion that the performance of drones as avian hazing devices will likely to depend on a combination of factors including platform selection, drone trajectory, duration of use, season, landscape context, and natural history of the pest species (Egan et al., 2023). In contrast to blackbirds, we want longer stay of larger flock of insectivorous birds which can feed on RSC and help in reducing pest-load. However, all the said factors affecting performance of drones against the blackbirds will also certainly come to affect (positively or negatively) the performance of drones to be used against insectivorous birds.

Multi-rotor drones are relatively easy to fly and are a multifunctional tool for agricultural use; however, they may not be an effective avian deterrent due to a lack of similarity in appearance with natural predators (Egan et al., 2023), but drone with "lack of similarity in appearance with natural predators" will be a desired criteria for insectivorous birds in the context of RSC outbreak.

Sampling the insects during outbreak of RSC

Pest monitoring is time-consuming and may be hampered by lack of reliable or cost-effective sampling techniques (Filho et al., 2019). Sampling of insect-pests is the base of population count and a determinant of decision making of pest management. Different drones have been recommended for scouting and sampling for minimizing cost, time and efforts for collecting live insects in agricultural fields and in most cases, researchers have suggested the sampling apparatus propelled by drone for adult stage of insect in crop ecosystem (Madden et al., 2022; Ryu et al., 2022). Researchers will have to develop drone based techniques to scout the larval populations of RSC during outbreak period. Collecting such larvae will not be possible by the samplers designed for aerial pests. Besides, the RSCs generally remain hidden at the base of the rice-hills during day time, but creep up to the top of the rice-plants with the inundation of the rice-fields with water. Thus, any survey on RSC during outbreak with drone must be initiated in low lying rice fields where larvae will be more visible on the top portion of rice plants as compared to that in upland. One while of designing a drone-based-sampler must look for such behavior of the pest while optimizing the operational parameters. Moreover, drone with high resolution camera for taking the image of larvae is a basic requirement in this context.

Assessing the actual infested area and advancing of the infestation-front

Floods carry the caterpillars from infested rice fields to uninfected ones and thus intensify the severity of RSC in newly flooding areas (Sarma et al., 2021). The entry point of streams carrying the caterpillars from upstream to paddy fields can easily be identified by drone based on the previous records of outbreak and periodic survey during flood. A drone can be an effective gadget to assess the actual infested area more effectively even during an extensive outbreak in large fields and can trace the caterpillars are carried into the paddy fields by downstream water. In both the said conditions, the outbreak infested area may be inaccessible to farmers, especially if the paddy field is too large and the level of inundation is very high. It becomes more difficult to locate and asses the infested area by conventional survey where birds-flocks are absent. Under such inaccessibility and absence of ecological service-providers, the drone can play a vital role in assessing the outbreak area.

Rapid assessment of crop damage during RSC outbreak

Rapid assessment of crop damage is essential for successful management of insect pest outbreaks (Park et al., 2023). Assessment of crop damage by drone during RSC outbreak is essential to curtail a few days of survey as compared to conventional ground survey. Such a "curtailment" would not only speed up the decision making, but also eliminate the insecticide-load to be added in those few days curtailed. Since it is a time saving method, it will alerts the farmers well ahead about the progressive RSC outbreak and help them take control measures.

Park et al. (2023) clearly demonstrated the effectiveness of using rotary-wing unmanned aircraft system (UAS) and image analysis to conduct a low-cost aerial survey of soybean damage caused by *Spodoptera exigua* (Hübner) outbreaks, and estimated defoliation of 78.3% with a range of 22.4–99.8% in 31 soybean blocks. They found the aerial survey and image analyses more economical than the conventional ground survey when the number of target soybean blocks was more than 15 blocks. RSC being a co-generic species to *S. exigua*, an initiative may be taken to assess such rotary-wing UAS against RSC as used by Park et al. (2023).

Filho et al. (2019) have specifically focused on use of small unmanned aerial robots, or small drones, in agricultural systems. Small size and weight of drone are two prime desired features for monitoring RSC during outbreak. Small drones will be more cost effective in mandatory monitoring of RSC hubs, seasonal surveys and scouting in extensive area during outbreak. Moreover, disturbance to flock of beneficial birds by a small drone will be less than that by a bigger one.

Optimization of operational parameters of drones in the context of RSC outbreak

Optimization of operational parameters of drones is prime requisites for effective sampling/survey of RSC and spraying insecticide to combat RSC outbreak. Many research works application of drone for pesticide spray in the rice ecosystem have been done in Asian countries (Qin et al., 2016; Chen et al., 2017, 2020; Wang et al., 2017; Yang et al., 2017; Kim et al., 2018; Yallappa et al., 2018; Guo et al., 2019; Li et al., 2019).

Subramanian et al. (2021) made a detailed review on different aspects of drone used in insect pest management in different crops and summarized the various applications of UAVs with the set of parameters (Flight height, Flight speed, Nozzle Type) for pesticides spray in various crops and their efficiencies in comparison to conventional sprayers in Table 2. They categorized various UAV types (Single rotor, multi-rotor, WWSSN UAV), range of flight height (0.98–5m), flight speed (0–10 m/s), nozzle type (hollow cone, flat cone, TEEJET, flat fan nozzle), spray drift (5–90%), and spray efficiency with a maximum coverage of 98.5% in rice canopy.

In India, the preliminary studies made at Tamil Nadu Agricultural University, Coimbatore to study the efficacy of fungicide spray in rice fields using hexacopter drone have shown the optimal flying height, speed, swath and the area coverage as 3 m, 5 m/s, 4 m, and 4 min/acre respectively (Subramanian et al., 2021).

Even though all these studies were conducted in paddies with non-outbreak situation for RSC (or other rice pest), a researcher may consider these outcomes as initial inputs for selection of drone type and setting up of the operational parameters; later on these can modified and optimized for outbreak situation of RSC.

Reliable spatial scale will help drones in forecasting

In order to improve forecasting of pest epidemics, it is important to determine the spatial scale at which local forecasts are reliable (Damgaard et al., 2019). In order to predict the outbreak at a local site, it will be useful to know how to best incorporate the information on population build up from near-by monitoring sites, RSC hubs or rice-fields, i.e., what is the spatial covariance of RSC outbreaks (Sarma et al., 2023a,b). There is no literature on such spatial scale for RSC outbreak and therefore, determination of such spatial scale will allow the researchers to use drones to forecast outbreaks in rice-fields in a realistic agricultural setting.

Few researchable issues pertaining to use of drone in RSC outbreak

The literatures on use of drone in crop ecosystems are many, but these are very few in the context of outbreak of insect-pest in rice ecosystem. Therefore, researchers may formulate for some research works in order to generate pertinent data. Few of such issues are—(i) Determination of the optimum flight-height and speed for clear visibility of the crop damage and presence of caterpillars on foliage; (ii) Real time assessment of pest attack through frequent inspection by drone in early & late vegetative crop of rice; (iii) Optimization of image related parameters such as optimum resolution of camera, height of drone platform etc.; (iv) Diagnosis and quantify of the negative impacts of movement of drones owing to its design, shape, size etc. to the movement and perching of insectivorous birds (or flock) and their feeding of RSC by these birds and other natural enemies.; (v) Region specific comparative economic analysis between with conventional method and drone technology for surveying and spraying of insecticide (quantity of insecticide and number of sprays).

From the published literatures, it is seen that most of the work on drones' application on monitoring and spraying insecticide over rice canopy are for management of Brown Plant Hopper, leaf folder etc. No work has been done on the use of drone against Rice Swarming Caterpillar because of its negligible presence and damage as a sporadic pest in non-outbreak season. However, more outbreaks of RSC are likely to occur in the future (Sarma et al., 2021). Therefore, we advocate use of drone for quicker monitoring of RSC followed by its prompt management during outbreak to minimize the crop damage. Addressing the above cited researchable issues will certainly make the use of drone technology systematic, effective and helpful through early decision making in combating the RSC outbreak which will in turn help the poor and marginal farmers, the ultimate victims of any crop-pest outbreak.

Author contributions

AS: Conceptualization, Writing – original draft, Writing – review & editing. CD: Writing – review & editing. MS: Writing – review & editing. PN: Writing – review & editing.

Funding

The author(s) declare financial support was received for the research, authorship, and/or publication of this article. The authors declare that financial support was received for the publication of this article from the Ministry of Higher Education and Science, Denmark (Grant Ref. no.: 0192-00001B).

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

All claims expressed in this article are solely those of the authors and do not necessarily represent those of their affiliated organizations, or those of the publisher, the editors and the reviewers. Any product that may be evaluated in this article, or claim that may be made by its manufacturer, is not guaranteed or endorsed by the publisher.

References

Amala, U., Sampathkumar, M., Ramanujam, B., and Ballal, C. R. (2019). *Crop Pest Report & Media Coverage*. Bengaluru: AICRP-BC; ICAR-NBAIR, 144.

Baruah, M. (2017). *Swarming Caterpillar: A Menace to Rice Farmers in Assam*. Cuttack: ICAR-IIRR News Letter, 36–37.

Berryman, A. A. (2008). "Outbreaks of insects," in *Encyclopedia of Entomology*, ed. J. L. Capinera. Dordrecht: Springer.

BettiSorbelli, F., Palazzetti, L., and Pinotti, C. (2023). "A drone-based automated *Halyomorpha halys* scouting: a case study on orchard monitoring," in *5th IEEE International Workshop on Meteorology for Agriculture and Forestry* (Pisa: IEEE).

Bjørnstad, O. N., Ims, R. A., and Lambin, X. (1999). Spatial population dynamics: analyzing patterns and processes of population synchrony. *Trends Ecol. Evol.* 14, 427–431. doi: 10.1016/S0169-5347(99)01677-8

Bouffanais, R. (2016). "Design and control of swarm dyanamics," in *SpringerBriefs in Complexcity (First Ed.)* (Berlin: Springer).

Carrasco-Escobar, G., Moreno, M., Fornace, K., Herrera-Varela, M., Manrique, E., and Conn, J. (2022). The use of drones for mosquito surveillance and control. *Parasit. Vect.* 15:473. doi: 10.1186/s13071-022-05580-5

Chen, S., Lan, Y., Zhou, Z., Ouyang, F., Wang, G., Huang, X., et al. (2020). Effect of droplet size parameters on droplet deposition and drift of aerial spraying by using plant protection UAV. *Agronomy* 10:195. doi: 10.3390/agronomy10020195

Chen, S. D., Lan, Y. B., and Li, J. Y. (2017). Effect of wind field below rotor on distribution of aerial spraying droplet deposition by using multi-rotor UAV. *Trans. Chin. Soc. Agricult. Mach.* 48, 105–113. doi: 10.6041/j.issn.1000-1298.2017.08.011

Damgaard, C., Bruus, M., and Axelsen, J. A. (2019). The effect of spatial variation for predicting aphid outbreaks. *J. Appl. Entomol.* 144, 263–269. doi: 10.1111/jen.12724

Egan, C. C., Blackwell, B. F., Fernández-Juricic, E., and Klug, P. E. (2023). Dispersal of blackbird flocks from sunflower fields: efficacy influenced by flock and field size but not drone platform. *Wildlife Soc. Bullet.* 47:e1478. doi: 10.1002/wsb.1478

Filho, F. H. I., Heldens, W. B., Kong, Z., and Lange de, E. S. (2019). Drones: Innovative technology for use in precision pest Management. *J. Econ. Entomol.* 20, 1–25. doi: 10.1093/jee/toz268

Fukagawa, N. K., and Ziska, L. H. (2019). Rice: importance for global nutrition. *J. Nutr. Sci. Vitaminol.* 65, S2–S3 doi: 10.3177/jnsv.65.S2

GRiSP (2013). *Rice Almanac*. Los Banos: International Rice Research Institute, 1–283.

Guo, S., Li, J., Yao, W., Zhan, Y., Li, Y., and Shi, Y. (2019). Distribution characteristics on droplet deposition of wind field vortex formed by multi-rotor UAV. *PLoS ONE* 14:e0220024. doi: 10.1371/journal.pone.0220024

Jena, M., Guru, P. P., Pun, K. B., Saikia, K., Rath, P. C., Basana Gowda, G., et al. (2017). *Swarming Caterpillar in Rice: Status and Their Management; NRRI Technology Bulletin-127*. Cuttack: National Rice Research Institute.

Kim, H. G., Park, J. S., and Lee, D. H. (2018). Potential of unmanned aerial sampling for monitoring insect populations in rice fields. *Fla. Entomol.* 101, 330–334. doi: 10.1653/024.101.0229

Li, X., Andaloro, J., Lang, E., and Pan, Y. (2019). "Best management practices for unmanned aerial vehicles (UAVs) application of insecticide products on rice," in *2019 ASABE Annual International Meeting, Session of Precision Aerial Spray Applications: UAV/Drones and Manned Aircraft* (Boston, MA: ASABE).

Liebhold, A., Walter, D. K., and Bjørnstad, O. N. (2004). Spatial synchrony in population dynamics. *Annu. Rev. Ecol. Evol. Syst.* 35, 467–490. doi: 10.1146/annurev.ecolsys.34.011802.132516

Madden, J. C., Brisson-Curadeau, E., Gillung, J. P., Bird, D. M., and Elliott, K. H. (2022). Optimal settings and advantages of drones as a tool for canopy arthropod collection. *Sci. Rep.* 12:18008. doi: 10.1038/s41598-022-22446-z

Mainali, R. P., Dangi, N., Aryal, S., Bhandari, G., and Bajracharya, A. S. R. (2014). Management of armyworm outbreak in rice field of chitwan district. *Asian J. Sc. and Tech.* 5, 774–776.

Moran, A. P. (1953). The statistical analysis of the *Canadian lynx* cycle II synchronization and meteorology. *Aust. J. Zool.* 1, 291–298. doi: 10.1071/ZO9530291

NRRI (2016). *Rice Swarming Caterpillar Devastates Winter Rice Fields in Assam*. Cuttack: ICAR-National Rice Research Institute, 9–10.

O'Loan, E. (1998). Alternating steady state in one-dimensional flocking. *J. Phys. A.* 32, 99–105. doi: 10.1088/0305-4470/32/8/002

Park, Y. L., Naharki, K., Karimzadeh, R., Seo, B. Y., and Lee, G. S. (2023). Rapid assessment of insect pest outbreak using drones: a case study with *Spodoptera exigua* (Hubner) (Lepidoptera: Noctuidae) in Soybean fields. *Insects* 14:555. doi: 10.3390/insects14060555

Pathak, M. D., and Khan, Z. R. (1994). *Insect Pests of Rice. International Centre of Insect Physiology and Ecology* (Manila: IRRI), 68.

Qin, W. C., Qiu, B. J., and Xue, X. Y. (2016). Droplet deposition and control effect of insecticides sprayed with an unmanned aerial vehicle against plant hoppers. *Crop Protect.* 85, 79–88. doi: 10.1016/j.cropro.2016.03.018

Ryu, J. H., Clements, J., and Neufeld, J. (2022). Low-cost live insect scouting drone: iDrone Bee. *J. Insect Sci.* 22:5. doi: 10.1093/jisesa/ieac036

Sampathkumar, M., Amala, U., Jalali, S. K., and Ballal, C. R. (2018). *Crop Pest Report and Media Coverage*. Bengaluru: AICRP-BC, ICAR-National Bureau of Agricultural Insect Resources, 37.

Sarma, A. K., Bhattacharyya, H. K., Ojah, H., and Sharma, K. (2013). "Outbreak of rice swarming caterpillar under the changing climatic conditions of Assam," in *Abstracts: National symposium on Climate Change and Indian Agriculture: Slicing down the Uncertainties* (Hyderabad: CRIDA), 226.

Sarma, A. K., Damgaard, C., and Neog, P. (2021). Retrospection of outbreaks of *Spodoptera mauritia* Boisduval in NER India: the solution lies in ecological engineering, not in insecticides. *Sustainability.* 13:12824. doi: 10.3390/su132212824

Sarma, A. K., Damgaard, C., and Neog, P. (2023a). "Prediction of local outbreaks of Rice Swarming Caterpillar: a need to protect the organic nature of rice cultivation in NER India," in *Abstracts: International Conference on Biodiversity, Food Security, Sustainability and Climate Change (ICBFSCC-2023)* (Jorhat: Assam Agricultural University), 110.

Sarma, A. K., Deka, M., and Kashyap, A. (2023b). "Drone-Netting for sampling insect-pests and vectors in agricultural landscape," in *Smart Agriculture: Digital Era in Farming, First ed.* (New Delhi: Elite Publishing House), 100–105.

Sarma, A. K., and Gupta, M. K. (2018). Favourable factors for outbreak of rice swarming caterpillar in Dibrugarh, Assam. *Indian J. Entomol.* 80, 698–702. doi: 10.5958/0974-8172.2018.00225.0

Sarma, A. K., and Salam, A. (2018). Outbreak of *Spodoptera mauritia* Boisduval in Assam. *Indian J. Entomol.* 80, 1646–1653. doi: 10.5958/0974-8172.2018.00271.7

Subramanian, K. S., Pazhanivelan,. S., Srinivasan, G., Santhi, R., and Sathiah, N. (2021). Drones in insect pest management. *Front. Agron.* 3:640885. doi: 10.3389/fagro.2021.640885

Tanwar, R. K., Anand, P., Panda, S. K., Swain, N. C., Garg, D. K., Singh, S. P., et al. (2010). *Rice Swarming Caterpillar (Spodoptera mauritia) and its Management Strategies; Technical Bulletin 24*. New Delhi: National Centre for Integrated Pest Management, 1–19.

Trujillano, F., Garay, G. J., Alatristash-Salas, H., Byrne, I., Nunez-Del-Prado, M., et al. (2023). Mapping malaria vector habitats in West Africa: drone imagery and deep learning analysis for targeted vector surveillance. *Remote Sens.* 15:2775. doi: 10.3390/rs15112775

Upamanya, G. K., Kalita, N., and Sarma, R. (2013). Incidence of swarming caterpillar in winter paddy in Barpeta district of Assam. *Insect Environ.* 19, 171–172.

Wang, S. L., Song, J. L., and He, X. K. (2017). Performances evaluation of four typical unmanned aerial vehicles used for pesticide application in China. *Int. J. Agricult. Biol. Eng.* 10, 22–31. doi: 10.25165/j.ijabe.20171004.3219

Yallappa, D., Veerangouda, M., Maski, D., Palled, V., and Bheemanna, M. (2018). "Development and evaluation of drone mounted sprayer for pesticide applications to crops," in *2017 IEEE Global Humanitarian Technology Conference* (San Jose, CA: IEEE), 1–7.

Yang, F. B., Xue, X. Y., Zhang, L., and Sun, Z. (2017). Numerical simulation and experimental verification on downwash air flow of six-rotor agricultural unmanned aerial vehicle in hover. *Int. J. Agricult. Biol. Eng.* 10, 41–53. doi: 10.25165/j.ijabe.20171004.3077