Bio-ecology of rice insect pests and diseases: Paving the way to climate-smart rice protection technologies

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SUMMARY

The insect problem is accentuated in intensive rice cropping where the insects occur throughout the year in overlapping generations. In India, about a dozen of insect species are of major importance in rice but the economic damage caused by these species varies greatly from field to field and from year to year. Insect pests cause about 10-15 per cent yield losses. Estimation states that farmers loose an average of 37% of their rice crop due to insect pests and diseases every year. This chapter focuses on literature generated on various aspects of rice insect pests, diseases *viz*., pest status and their distribution, bio-ecology, diversity, forecasting model for real-time pest-advisory services, hyper-spectral remote sensing in pest damage assessment, impact of climate change on insect biology, population structure and epidemiology of different rice diseases.

1. INTRODUCTION

The rice plant is an ideal host for large number of insects and pathogens right from nursery to harvest, but only a few of them are considered to be the serious pests those cause economic losses by minimizing the attainable yields. About 800 insect species attack rice starting from their production to consumption and the rest are all friendly insects. Both the mature and immature stages of insect damage rice plants by chewing leaves and root tissues, boring and tunnelling into stems or sucking sap from stems and grains. The injury from feeding leads to damage showing symptoms of skeletonized and defoliated leaves, dead hearts, white ear heads, stunted and wilted plants and unfilled grains. Ultimately insect damage affects the plant physiology leading to reduction in measurable yield, utility or economic return.

In India, about a dozen of insect species are of major importance but the economic damage caused by these species varies greatly from field to field and from year to year. These species include stem borers [yellow stem borer (*Scriphophaga incertulas*), white stem borer (*Scirphophaga innotata*), pink stem borer (*Sesamia inferens*), stripped stem borer (*Chilo polychrysus*), dark-headed stem borer (*Chilo suppressalis*)], leaf folder (*Cnaphalocrocis medinalis* (Guenee), brown planthopper (*Nilaparvata lugens* Stal.). In addition, species distribution and abundance vary among rice

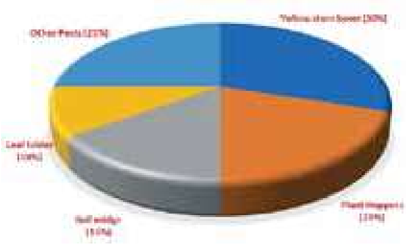

Fig. 1. Estimated yield losses due to different insect pests in rice in India (Modified from http://www.rkmp.co.in

ecosystems within a given ecology. For example, termites are primarily upland rice feeders while others are more numerous and damaging under lowland conditions. Some species like yellow stem borer, leaf folder, brown plant hopper may be abundant in all rice-growing environments. Among the biotic stresses insect pests cause about 10-15 per cent yield losses. At National level, stem borers accounted for 30% of the losses, while planthoppers (20%), gall midge (15%), leaf folder (10%) and other pests (25%) accounted for rest of the losses (Krishnaiah and Varma, 2018) (Fig. 1).

Among the various diseases reported, blast, bacterial blight, sheath blight, stem rot, brown leaf spot and false smut were recorded to be the significant ones. Of these, the sheath blight, bakane and false smut became important only after the green revolution. Some of the diseases appeared in few pockets became major constraints are sheath rot, seedling mortality by *Sclerotium rolfsi*. Primary source of inoculum are internally seed borne, bacterial blight, blast, brown spot, sheath rot (fungal and bacterial), seedling elongation, foot rot, seedling rot by *F. moniliforme*; externally seed borne or as admixture in seed are sheath blight, false smut, seedling blight by *Sclerotium rolfsi.* Some of the soil borne diseases are seedling elongation, foot rot and seedling rot by *F. moniliforme*; sheath blight, false smut, seedling blight by *Sclerotium rolfsi*. Besides the above, all the diseases may spread through collateral host/stubbles of infected plant/diseased plant parts left in the field. Collectively, rice diseases result in yield reductions of 10-15% in tropical Asia.

Crop losses due to arthropods, diseases and weeds across the world have increased from about 34.9% in 1965 to about 42.1% in the late 1990s and the trend is very alarming. Indian farmers face many biotic constraints in their mission to increase rice production. This chapter focuses on literature generated on various aspects of rice insect pests, diseases *viz*., pest status and their distribution, bio-ecology, diversity, use of hyper-spectral remote sensing in pest damage assessment, impact of climate change on insect biology, population structure and epidemiology of different rice diseases.

Biodiversity conservation has always been major concern and in recent research on this theme has been directed to areas under direct human influence such as agricultural areas where biodiversity performs important functions for productivity through recycling nutrients, regulating the micro-climate and the hydrological processes (Mohapatra 2014). Majority of rice pests are controlled by a complex and rich web of predators and parasitoids that live in or on the rice plant, rice water or soil. The techniques to enhance the biodiversity will enable us to better utilizing the ecological engineering method and opportunities for biodiversity conservation associated with rice fields. There is a need to develop forewarning system, which can provide advance information for outbreak of insect pests and diseases. Limitation of forewarning model for specific geographic locations could be overcome by the use of satellite-driven weather and agromet data. Resultant systems shall enable appropriate agro-advisory to minimize application of chemical pesticides, losses due to insect pests and diseases, financial burden and environmental cost. Remote sensing gives a synoptic view of the area in a non-destructive and non-invasive way which could be effective and provide timely information on spatial variability of pest damage over a large area. The role of hyperspectral remote sensing in pest surveillance can guide scouting efforts and crop protection advisory in a more precise and effective manner.

A successful pest management plan requires information about a species biology and lifecycle, how it interacts with other species. One pathogen lesion on one leaf does not have a significant economic or ecological impact, however, during an epidemic case even a single lesion leads to causes significant crop loss involves thousands or millions of infections to their host plants. Epidemiology focuses on disease progression, the multiplication of pathogen population through time and the movement of pathogen population from plant to plant. Hence, it is important to understand the population biology and epidemiology of pathogen in order to develop rational control strategies.

To manage the above problems, the present chapter is discussed on the four objectives.

i. Studies on the faunal diversity *viz*., insect pests, soil arthropods and natural enemies in different rice ecologies

ii. Standardization of hyperspectral signature for candidate pests and develop satellite based fore-warning model for major rice pests

iii. Studies on the population structure of pathogens in different rice ecologies

iv. Studies on the epidemiology of major and emerging rice diseases

1.1. Faunal diversity in rice field

Rice fields together with their contiguous aquatic habitat and dry land comprise changing ecotones, harboring a rich biological diversity, maintained by rapid colonization as well as reproduction and growth of organisms. The variety of organisms inhabiting rice ecosystems includes micro, meso and macro invertebrates (especially arthropods) inhabiting the vegetation, water and soil sub-habitats of the rice fields. In addition, many species of amphibians, reptiles, birds and mammals visit the rice fields for feeding from surrounding areas and are generally considered as temporary or ephemeral inhabitants (Bambaradeniya et al. 1998). In relation to the rice crop, the fauna and flora in rice fields include pests, their natural enemies (predators and parasitoids) and neutral forms.

1.2. Lowland rice ecosystem

The rice plant is a host for insects as diverse in their feeding habit as polyphagous grasshoppers and the virtually monophagous white backed plant hopper, *Sogatella* *furcifera*. Chakraborty et al (2016) profiled the arthropods from the rice field of Upper Gangetic Plain of West Bengal revealed that that herbivores (41%) topped the list followed by predators (21%), parasitoids (16%), detrivours (13%) and plankton feeders (9%). In predatory guild, spiders were dominant group occupied over 41% followed by Coleoptera (29%), Hemiptera (8%), Odonata (8%), Diptera (5%), Hymenoptera (6%) and Neuroptera (2%) in descending order (Fig. 2). On-farm IPM trial on rice conducted in rainfed low land ecosystem in the Pipili block of Puri district in Odisha revealed that under IPM regime, predator like damsel fly, ground beetle (*Paedarus* sp.), spiders (*Pardosa pseudoannulata, Tetragnatha* sp., *Neoscana theisi*) and mirid bugs were more compared to farmers' practice. The same trend was observed in case of parasitoid complex comprising of *Apanteles* sp. and *Cardiochiles* sp. (Mohapatra et al. 2016). Diversity indices of insect pests and natural enemies differed according to different cultural practices, ecologies and crop growth stages. The highest abundance was at reproductive stage and lowest was at mid tillering stage. They also found that transplanted rice fields are richer both in species diversity and species richness. Bakar and Khan (2016) reported that early tillering stage showed higher diversity in terms of diversity index (1.48) compared to other three stages (Fig. 3).

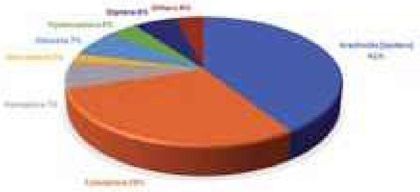

Fig. 2. Abundance of arthropod natural enemies in rice at Upper Gangetic Plain of West Bengal

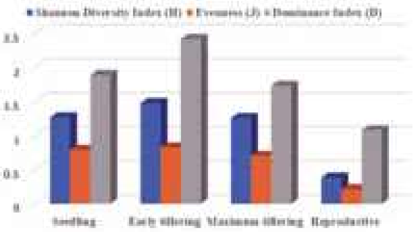

Fig. 3. Diversity indices, evenness and dominance of insect pests at different stages of rice at Bangladesh

Evenness was also highest in the same stage (0.826) indicating the highest equability among insect pests in that stage. The values of D also differed within different stage and appeared as the highest at early tillering stage (2.42) and lowest at reproductive stage (1.08).

However, 3 diversity indices viz., diversity index (H), evenness (J) and D were found highest at early tillering stage thus seemed to be more stable than other. Similarly, they also reported that the diversity indices viz., diversity index (H), evenness (J) and D of natural enemies in boro rice at different stages were found highest at seedling stage and the lowest at early tillering stage (Fig. 4). Arthropod diversity study undertaken at ICAR-National Rice Research Institute, Cuttack in semi-deep water and irrigated low land ecologies revealed that in semi deep water rice ecology, spiders (7.2/sweep) outnumbered the other predatory groups and were widely distributed throughout the study area. The other major predatory arthropods include damsel fly (5.9/sweep) and lady bird beetle (5.2/sweep).

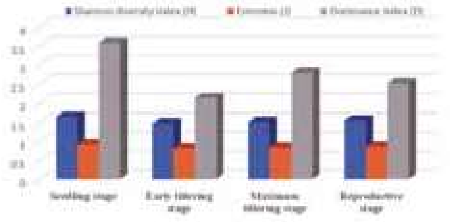

Fig 4. Diversity indices, evenness and dominance of Natural enemies community at different stages of rice at Bangladesh

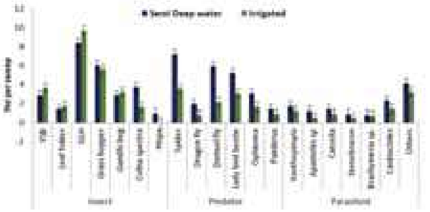

Fig. 5. Diversity of insect pests and natural enemies in semi-deep water and irrigated rice ecosystems at NRRI, Cuttack

Among the parasitoids, *Xanthopimpla* sp., *Carcelia* sp., *Stenobracon* sp. *Apanteles flavipes*, *Brachymeria* sp., *Cardiochiles* sp. were the predominant one occurred (Fig 5).

Although the same trends were observed in the irrigated ecology, but the number was comparatively lower than semi deep-water ecology. Diversity indices computed in irrigated ecosystem were Simpson's index [1/D] (10.48), Shannon-Wiener index [H'] (2.62), Margalef's index [M] (2.75) whereas in semi deep water ecologies the Simpson's index [1/D] (13.42), Shannon-Wiener index [H'] (2.78) and Margalef's index [M] (2.76). (NRRI Annual Report 2015-16).

1.3. Coastal rice ecosystem

Coastal rice ecosystem consists of both irrigated uplands and low lands. An experiment conducted at Srikakulam district during *kharif* 2017 depicted that during the first 30 days after transplanting significant yield losses occurred due to BPH, WBPH and leaf folder in low lands of coastal ecosystem. The crop growth period between 30-60 days after transplanting was most vulnerable resulting in major yield losses (20-60%) mainly due to stem borer, leaf folder and brown planthopper. Beyond sixty days after transplanting, the crop damage is inflicted by stem borer and leaf folder causing 10 to 48% damage in coastal ecosystem. The other beneficial fauna prevalent in the coastal ecosystems are coccinellid beetles (5 species), spiders (4 species), earwigs (3 species) and lacewings (2 species). The biocontrol agents include egg parasitioids (2 species) in the coastal ecosystem in north coastal Andhra Pradesh.

1.4. Ratoon rice

A ratoon crop is potentially at risk from insect pests because it extends the time period of host availability. With its shortened vegetative stage, a ratoon crop is unsuitable to early season insects like whorl maggot, *Hydrellia philippina* and caseworm, *Nymphula depunctalis.* Stem borer numbers are significantly reduced at main crop harvest, but some survives to attack the ratoon crop. Leaf folder infestation is higher at the vegetative stage on a ratoon crop than main crop. The lack of land preparation in establishing a ratoon crop allows a high carryover of natural enemies, particularly the predators which prevent significant build up of brown planthopper, white backed planthopper and green leafhopper.

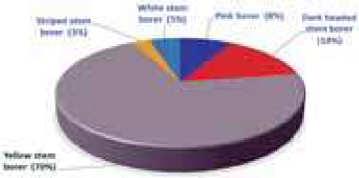

Fig. 6. Relative abudance of different species of stem borer

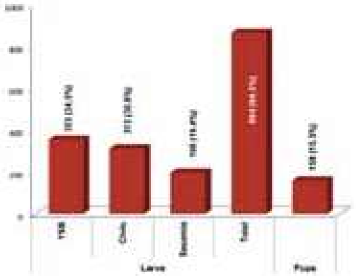

Fig. 7. Abundance of rice stem borer in stubbles in ICAR-NRRI, Cuttack

The incidences of diapausing rice stem borer larvae in the rice crop residues (stalks and stubbles) investigated at ICAR-NRRI, Cuttack from December 2016 to March 2017 revealed that three predominant stem borer larvae diapaused in the rice crop residues were Yellow stem borer, *Scirpophaga incertulus,* Striped stem borer, *Chilo supressalis and* Pink stem borer*, Sesamia inference.* The relative abundance of three diapausing stem borers revealed that yellow stem borer (40.8%) was most predominant followed by Striped stem borer (36.2%) and Pink stem borer (23%). The occurrence of stem borer species was correlated with the height of the stubble. The results revealed that 60% of the total *S. inferens* and 17.6% of the total *Chilo* sp recorded were concentrated to 9.8 and 7.0 cm above the root zone, respectively, whereas 98% of the Yellow stem borer larvae were concentrated to the base of rice stubbles (Fig 6 & 7).

It is clear that destruction of diapausing larvae of the above species of rice stem borers during land preparation would be an effective cultural control method (NRRI Annual Report 2015-16). During crop harvest, if rice stubble heights are adjusted to a range of 5–10 cm, the survived stem borers can be reduced by 70–90%. Furthermore, approximately 70% of the overwintering stem borers can be killed by ploughing and irrigation. These measures can significantly decrease the initial population sizes of stem borers.

1.5. Natural enemies

In agro-ecosystems, the associated natural enemies can perform important ecological services, mainly biological control of crop pests. Naturally occurring biological control has a potential role to play in the management of rice fields of tropical south and south-east Asia and there is a need to emphasize the impact of indigenous natural enemies as an essential part of IPM programme. Conservation of the natural enemy fauna in situ for suppressing the pest population seems to be a very good alternative. A study conducted at Cauvery command areas of Karnataka by Parasappa et al. (2017) indicated that among the various predators, spiders and mirids were the most important natural enemies. Among the odonata, damselflies population was more compared to the dragonflies. Mirids *Cyrtorhinus lividipennis* was considered as important, potential and efficient predator of BPH and WBPH. Staphylinids were identified as *Paederus fuscipes* which is a predator on leafhoppers. Rice insect predators in India belong to 25 families of 6 orders of class Insecta. Among the predacious orders, Coleoptera ranks first and the family Coccinelidae is exclusively predacious with a few exceptions. Predaceous carabid beetles are generally recognized as useful natural enemies against lepidopterous larvae in the rice fields. There are 368 coleopteran species associated with rice and there is always confusion about their herbivorous or beneficial role. Hymenopterous parasitoids associated with rice are 524 species belonging to 181 genera exercising natural control. Among the 419 organisms enumerated during the investigation, hymenopterans were by far the most abundant representing 191 species followed by coleopterans and dipterans representing 38 species each.

Predators are the most conspicuous and consume many preys during their life span. Dragon flies and damsel flies are amongst the most conspicuous insects associated with irrigated rice fields. They predate on adults of yellow stem borer and leaf folders. Fourteen spp. of dragonflies and damselflies have been recorded from rice field at Cuttack.

1.5.1. Spider: Spiders such as the wolf spider, Lynx spider, Orb spider are known to consume a large number of prey and play an important role in reducing the densities of plant and leaf hoppers in rice fields. Spiders are thus known as biological control agents for phytophagous insects with some species being able to reduce the total pest population by 22% per day. The predominant species of predatory spiders were reported from rice fields of North–Eastern UP were *Tetragnatha javana*; *Pardosa pseudoannulata*; *Tetragnatha mandibulata*, *Pardosa birmanica*, *Hippasa holmerae*, *Tetragnatha maxillosa*,

1.5.2. Bird: In rice cultivation, many farmers have the practice of keeping dried tree stumps in different localities in the field. Birds such as Drongos, Mynas and Kingfishers use perches to feed on insects and caterpillars from the rice fields during daytime. At night, different species of owls use these perches to prey upon rodents that contribute to crop loss. Another group of birds that play a vital role in rice fields is the Egrets, Herons and Water hen. These birds feed on worms, moths and caterpillars as well as harmful soil organisms. Flock of cattle egret, *Bubulcus ibis* running behind the plough or country plough is a very common sight in the rice paddy.

1.5.3. Earthworm: Earthworms are the most important soil dwelling organisms involved in the process of soil formation and maintenance of soil health and help the composting process. Earlier ten different earthworm species have been identified from different habitats belonging to 4 different families. *Lampito mauritii* and *Pellogaster bengalensis* were found to be ubiquitous. Among them, only *L. maurtii* was found in all sites in high numbers

1.5.4. Duck: Ducks are generalist predators, feeding on stem borers, leaffolders, grasshoppers, planthoppers and leafhoppers etc. Ducks have big appetite and on an average one duck can consume more than 100 insects per hour thus decreasing pest populations quickly, particularly in the early to mid-tillering stage of rice. The total number of plant hoppers and leafhopper in duck fields were reduced by 63.9 and 77.3%. Rice–duck farming agro-ecosystem reduced 30.6% fertilizers and 59.4% pesticides usage compare with conventional farming system.

1.5.5. Fish: Fishes like carp, tilapia and catfish feed on plant and leaf hoppers, stem borers or other insects like mosquito larvae and other aquatic insects that fall into the water. Some fish also feed on the outer leaf of the leaf sheath, which contains plant hopper and leaf hopper eggs.

1.5.6. Soil arthropod: Soil mesofauna which includes Cryptostigmatids, soil Acari including Oriebatid and Cryptosigmatid mites and other invertebrates as important reservoir of biodiversity and plays a pivotal role in determining many soil characteristics. This diverse group of animals cover a range of taxa, the most important being protozoan's, nematodes, oligochaete worms (earthworms and enchytraeids), mites, collembolans, millipedes, centipedes and a range of insects whose larval stages complete their development in the soil. The presence of soil fauna increased the soil organic carbon and also helps in decomposition of organic matter which led to an increase in the yield of the crop by increasing the availability of nutrient. Some of soil arthropods like ants and termites increased soil water infiltration due to their tunnels and improved the soil nitrogen recycling of crop residues and plant productivity and keeping the balance of soil carbon pool as well.

2. FORECASTING MODEL FOR MAJOR INSECT PEST AND DISEASE

Weather-based forecasting systems reduce the cost of production by optimizing the timing and frequency of application of control measures for minimizing crop loss and reducing cost of plant protection. Forecast models provide an alternative to calendar spray schedule to bring need-based protection, e.g., instead of sprays at 7-14-day intervals to spray at precise time just when and where the pest is likely to appear. Thus, precision pest management may bring down number of chemical pesticide sprays to provide economic and environmental benefits. Finally, the system of forecast should be taken as economically acceptable action as an integral part of IPM package while growers should be capable and flexible enough to take due advantage of a pest forewarning advisory.

2.1. Stem borer

Rice yellow stem borer, *Scirpophaga incertulas* recorded were used in conjunction with the weather data of a particular location for development of weather-based prediction categorized as to low, medium and high severity. The weather-based criteria and prediction rules have been integrated online for forewarning *S. incertulas* population levels. Forewarning of *S. incertulas* is specific for Cuttack location for *kharif* season and being used for pest advisory services for the rice growers of the region.

2.2 Rice blast

Savary et al. (2012) in Korea developed EPIRICE, a generic model for plant diseases which was coupled with GIS. Manibhushanrao and Krishnan (1991) developed EPIBLA (EPIdemiology of BLAst) model using multiple regression equation based on maximum temperature and maximum RH for simulation of leaf blast incidence. In their model simulated incidence of blast made 7-day forecasts of disease progression in many parts of India. The ICAR- NRRI, Cuttack operated a simple leaf blast forecasting system based on empirical factors which interacted with rice varieties. Stages which are most susceptible to rice blast viz. seedling, tillering and flowering were identified. Kaundal et al. (2006) introduced a machine learning techniques model for forecasting rice blast in India. Six weather variables were selected viz. temperature (max and min), RH (morning & evening), rainfall and rainy days per week. Blast is mostly preferred by particular air and soil temperatures, relative humidity (RH), hours of continuous leaf wetness (LW), degree of light intensity, duration and timing of dark periods. All of these have been considered as very crucial for development of the disease.

3. HYPER SPECTRAL REMOTE SENSING FOR PEST SURVEILLANCE

At present, satellite remote sensing data are also being used in generating and improving weather forecasts, providing crop estimate in terms of net sown area and yield, issued in operational mode for the last few years with reasonable accuracy for rice, wheat, mustard, potato, etc. Use of Remote Sensing (RS) and Geographic Information System (GIS) could be explored for analysis of satellite-based agro-met data products, mapping geographical distribution of pests and delineating the hotspot zones. Super-imposition with causative abiotic and biotic factors on visual pest maps can be useful for pest forecasting. Since, damaged plants increase reflectance particularly in chlorophyll absorption band (0.5-0.7 cm) and water absorption bands (1.45-1.95 cm), forecasting crop pests is possible by remote sensing.

4. CLIMATE CHANGE AND RICE INSECT PESTS

Current estimates of changes in climate indicate an increase in global mean annual temperatures of 1 °C by 2025 and 3 °C by the end of the next century. The date at which an equivalent doubling of CO_2 will be attained is estimated to be between 2025 and 2070, depending on the level of greenhouse gases emission. Fifteen studies of crop plants showed consistent decreases in tissue nitrogen in high CO_2 treatments; the decreases were as much as 30%. This reduction in tissue quality resulted in increased feeding damage by pest species by as much as 80% (Coviella and Trumble 1999). In general, leaf chewers (Lepidoptera) tend to perform poorly whereas suckers (aphids) tend to show large population increases indicating that pest outbreaks may be less severe for some species but worse for others under high CO_2.

Natural enemy and host insect populations may respond differently to the global warming. There also instances where warmer conditions increase the effectiveness of many natural enemy species and/or increase the vulnerability of their prey. In extreme conditions, higher abundance of insect pests may partly be due to lower activity of parasitoids or to disturbed parasitoid-pest relationship and decreased controlling ability. However, parasitoids [*Anagrus incarnatus* and *Apanteles chilonis*] and predators (*C. lividipennis*), other than spiders (*Pardosa astrigera* and *Tetragnatha vermiformis*) of rice insects breed two to three more generations a year. These facts imply that the extent of biological control of rice pests by natural enemies will increase in intensity under the global warming.

4.1 Carbon dioxide

The majority of plants, particularly those in the C_3 category, which includes rice, respond to increased CO_2 levels by increasing productivity in the form of carbon fixation. A CO_2 induced reduction in host plant quality resulted in increased larval consumption rates in order to obtain adequate dietary nitrogen in generalist. In the majority of cases, increased feeding rates do not compensate fully for the reduced quality of the diet, resulting in poor performance, slowing insect development and increasing length of life stages which place them vulnerable to the attack by parasitoids. However, the change in C:N ratio in the plant, phloem sap becomes more concentrated at higher temperatures, and thus acts as a richer source of amino acids for sap feeders. The concentration of a range of secondary plant compounds tends to increase under drought stress, leading to changes in the attraction of plants to insects. The atmospheric environment in the future is predicted to include correlated increases in CO_2 concentration and temperature. While crop biomass is predicted to increase in response to elevated CO_2 concentrations under many circumstances, it is also recognized that crops and soils may subsequently become nutrient limited, especially in terms of nitrogen availability.

4.2 Temperature

Insects are ecto-thermic organisms, the temperature of their body changes approximately with the temperature of their habitats. Therefore, temperature is probably the most important environmental factor influencing their behaviour, distribution, development, survival and reproduction.

4.2.1 Yellow stem borer

Yellow stem borer took 8.1 mean days for hatching out into larvae at 30 °C. However at higher temperature hatching period was found to be decreased. In the same way, larval and pupal developmental period changes with increasing temperature. The percentage incidence of dead heart and white ear heads were correlated negatively with rainfall and minimum temperature, and positively with maximum temperature. The percentage of white ear head correlated negatively with relative humidity. Manikandan et al. (2013) reported that the number of eggs laid by YSB increased at higher temperature. At 28.3 °C, the YSB laid 143 eggs, whreas it was increased to 176.5 eggs at 36 °C with a standard deviation of 6.6. Insect populations from environments with higher temperatures may have higher fecundity and shorter growth stage. It is reported that the incubation period of *Scirpophaga incertulas* decreases at higher temperature, beginning at 30 °C and continuing up to 35 °C. Egg hatching percentage of the YSB decreased at higher temperature and increased at lower temperature. The egg hatching percentage was high (90.6%) at 30.6 °C followed by 28.3 °C. In contrast, only 58.5 per cent of incubated eggs achieved emergence at 36.0 °C. The incubation period of YSB eggs was 8.5 days at 28.3 °C, whereas it took only 5.75 days at 36 °C.

The development time taken by the four larval instars varied significantly with respect to the temperature.

4.2.2 Brown plant hopper

Brown plant hopper requires 6.7 mean days for hatching out into nymphs in ambient condition. However, this period decreased significantly at higher temperature. Decreased developmental duration of instars observed at increasing temperatures might be connected with faster larval growth at these temperatures. Insects develops faster will oviposit early and hence the population will grow earlier than expected. The total life span at 38 °C decreased significantly than at 30 °C.

4.2.3 Leaf folder

Drastic changes in temperature can cause oxidative stress, which in turn trigger the production of reactive oxygen species (ROS) derived from the metabolism of molecular oxygen which cause oxidative harm to proteins, nucleic acids, lipids. Insects produce a number of antioxidant enzymes for detoxifying ROS. Oxidative stress enzymes viz., glutathione s-transferases (GSTs), catalase (CAT), superoxide dismutase (SOD) play an inevitable role in detoxifying mechanism of ROS and contribute to regaining the balance.

One response to warm stress is the formation of reactive oxygen species (ROS) causing oxidative harm. The raised levels of SOD and GSTs movement, shown in a period played an important role in battling of ROS in *Neoseiulus cucumeris* demonstrated the contribution of these enzymes in host protection against thermal stress. The ability of an insect without compromising the pace of its growth and development to tolerate the thermal stress is an important adaptation to survive in various climatic conditions (tropical, subtropical, and temperate), which is vital in predicting insect outbreaks.

4.2.4 Stored grain pests

The stored grains maintained at a sufficiently low moisture level can be stored for many years without any significant loss in quality. Optimum grain moisture for development and reproduction of insects is 12.0 to 14.0 per cent. Generally, the dormant stages-eggs and pupae of insects, eggs and resting stages of mites, and spores of fungi can best resist desiccation while acting feeding stages may die out if conditions are too dry.

Angoumois grain moth is one of the most serious pests of stored rice (paddy) at post-harvest level. Three temperature zones are significant for growth and death of stored product insects. At optimal temperatures (25-32 °C), insects have maximum rate of multiplication. At sub optimal temperature (13-24 °C and 33-35 °C) where development slows, and at lethal temperatures (below 13 °C and above 35 °C) triggered the insects to stop feeding, develop slower, and eventually die. The more extreme temperature, the more quickly they die. Each insect species, stage and physiological state will affect the particular response to temperature. No stored-product insects can survive freezing.

Stored product insects breed faster at high humidity (65-80%) which is approximately equal to 13.0 – 15.0 per cent moisture content of the grains. Above 80 per cent humidity or 15 per cent moisture content, mould growth start suppressing insect multiplication. Rice weevils complete their life cycle in 25 days at 30 °C and while they take about 94 days at 18 °C. At a temperature over 34 °C, insects usually cannot develop. However, lesser grain borer *Rhyzopertha dominica* has the shortest development period of 25 days at 36 °C with 80.0 per cent relative humidity and longest development period of 106 days at 20 °C with 60.0 per cent relative humidity. At 20 °C developmental activities of larvae and pupae of *Tribolium castaneum* ceased and at 35 °C, it retarded significantly. The highest population increase of *S. cerealella* occurred at 30 °C.

4.3 Elevated temperature and carbon dioxide

Earlier studies predicted that elevated CO_2 and temperature exhibited a significant positive effect on BPH multiplication and its population than ambient CO_2 and temperature (Pandi et al. 2016). Rice plants exposed to elevated conditions recorded higher number of eggs (303.2 ± 35 eggs/female) whereas in the plants under ambient condition (212.9 ± 21.5 eggs/ female) female laid significantly less number of eggs. Thus, it was revealed that elevated condition stimulated fecundity of BPH by 29.5 % compared to ambient. Quantification of honeydew was directly related to the sucking rate; where only under elevated CO_2 condition honeydew excretion was significantly higher than ambient condition. In contrast elevated CO_2 and temperature honeydew excretion did not differ significantly from ambient condition. Further, developmental period of nymphs and longevity of brachypterous females were significantly reduced under elevated condition as compared to ambient. It has been observed earlier that every degree rises in global temperature, the life cycle of insect would be shorter. The quicker the life cycle, the higher will be the population of pests. Combined effects of both elevated temperature and CO_2 altered the plant phenology and pest biology and aggravated the damage by brown planthoppr (BPH), *Nilaparvata lugens.*

4.4. Precipitation

Many pest species favour the warm and humid environment. Both direct and indirect effects of moisture stress on crops make them more vulnerable to be damaged by pests, especially in the early stages of plant growth. Some insects are sensitive to precipitation and get killed or removed from crops by heavy rains. A decrease in winter rainfall resulted in reduced aphid developmental rates because drought-stressed tillering cereals reduce the reproductive capacity of overwintering aphids.

5. POPULATION BIOLOGY OF RICE PATHOGENS

5.1. Rice blast

Magnaporthe oryzae (63 isolates) collected, of which 16 (25%) were the mating type MAT1-1 while 35 (56 %) were mating type MAT1-2. The MAT1-2 isolates predominated in Jharkhand and Assam while MAT1-1 is more predominant in the isolates of Odisha. Both MAT1-1 and MAT1-2 were equally distributed in the isolates of Meghalaya and Tripura. In another study forty six isolates of *M. oryzae* were collected from various ecosystems of coastal Odisha, and the mating type analysis showed that MAT1-1 mating type was dominating in all the ecosystems and MAT1-2 was found to be present in uplands as well as in irrigated fields. Both mating types could be found in the same field in irrigated ecosystem.

Recently, twenty isolates of *M. oryzae* were collected from Chhattisgarh and categorized into three groups based on colony colour *i.e.*, greyish blackish, greyish and white, and in two group based on the texture of the colony as smooth and rough. All the twenty isolates produced the characteristics symptoms of spindle shaped lesion on susceptible plant. Among them, 5 isolates were found to be highly virulent, 8 were moderately virulent while, 7 were mild in nature. In phylogenetic analysis, overall two major groups were formed. The Chhattisgarh (CG-2 and CG-43) blast isolates along with Indian isolate were in one group whereas; isolates from Brazil, Kenya, Japan and China were in a separate group.

5.2. Sheath blight

Sheath blight (ShB) of rice caused by *Rhizoctonia solani* Kuhn [teleomorph: *Thanatephorus cucumeris* (Frank) Donk] is a major biotic constraint of rice in almost all the rice growing tracts of India. Yield losses due to this disease were estimated to range from 1.2 to 69.0% depending on the cultivar, environmental condition and crop stage. The pathogen has a wide host range and can infect plants belonging to more than 32 families and 188 genera. The weeds in and around the rice fields, water channel and irrigation ponds may serve as source of primary inoculum of the fungus. Natural occurrence of *Rhizoctonia solani* has been reported on sugarcane, weeds, wheat, bajra, cash crops such as cotton, coriander, and turmeric. Sheath blight pathogen survives from one crop season to another through sclerotia and mycelia in the plant debris and also through weed hosts in tropical environments. Both mycelia and sclerotia survive in infected plant debris. The disease severity was positively correlated with sandiness of soil. Further, the disease incidence was highest in wet soils with 50-60% water holding capacity (WHC) and lowest in submerged soils with 100% WHC.

The extent of damage of rice seedlings due to sheath blight incidence is dependent on resistance levels among the rice strains, average daily temperature and frequency of rain. Pot culture studies on the susceptibility of rice seedlings to *R. solani* revealed that disease incidence and development was rampant on 20 to 30 days-old rice seedlings compared to seedlings of 30 to 40 days old under artificially inoculated conditions. Rice ShB symptom production under artificial condition depends on the method of inoculation. Of different inoculation techniques such as single grain insertion, single sclerotium insertion and mycelial suspension injection; single sclerotium insertion was found most effective with highest ShB symptoms (68.5 to 80.0%), lesion length (2.45 to 4.75 cm) and percent disease index (32.5-43.5) followed by single grain insertion technique.

Maximum disease severity was observed when sheaths and leaves were inoculated with 7-day-old propagules of the pathogen. The amount of *R. solani* inoculum plays a major role in ShB disease development. Inoculum at the rate of 0.2 mg when placed inside the leaf sheath with a few drops of sterile water induced single, discrete and uniform-sized lesions irrespective of the inoculum type (mature, immature sclerotium, and mycelium). Early infection on a healthy plant within 12 h is possible when mycelium of the pathogen was used instead of sclerotial bodies. The ShB pathogen can infect the rice crop at any stage of growth from seedling to flowering by different inoculum sources. Three pathogens are found to cause ShB disease in rice. They are *R. solani* (*Thanatephorus cucum*eris), *R. oryzae-sativae* (*Ceratobasidium oryzae-sativae*) and *R. oryzae* (*Waitea circinata*). Combined inoculation with these pathogens resulted in highest disease severity. Further, ShB incidence was maximum when treated with *R. solani,* moderate with *R. oryzae-sativae*, and low with *R. oryzae*. Multiple linear regression test was made between the percent disease incidence (PDI) and the weather parameters indicating the highest contribution (61.05%) came from rate of evaporation, while the other two weather parameters *viz*., maximum and minimum temperature contributed 9.03% and 23.03% respectively.

5.3. Bacterial blight

The monitoring of pathotype is still an important tool for providing timely information about the population structure of the pathogen and the effect of climate change on population structure. In a recent study Yugander et al. (2017) reported that bacterial blight pathogen, *Xanthomonas oryzae pv oryzae* has invaded into the newer areas with more virulence. In fact the evolution of new races in plant pathogen is a continuous process which requires regular monitoring. The change of climate especially the increase of temperature with high humidity has helped the *X. oryzae pv oryzae* to gain more virulence and that's why newer areas were also invaded by this pathogen. It is interesting to observe that different researchers have reported presence of different pathotypes of X. *oryzae pv oryzae* in India (Nayak et al, 2008; Yugander et al. 2017) for further study on the pathogen population infecting rice with the help of differentials and molecular markers available.

5.4. Sheath rot

The rice sheath rot has gained the status of a major disease of rice and yield loss varies from 3 to 85%. Rice sheath rot is a disease complex that can be caused by various fungal and bacterial pathogens. Major pathogens associated with rice sheath rot disease are fungi such as *Sarocladium oryzae* and *Fusarium* sp. belonging to the *Fusarium fujikuroi* complex and the bacterial pathogen *Pseudomonas fuscovaginae* (Bigirimana et al. 2015). *S. oryzae* is present in all rice-growing countries worldwide, being very common in rainy seasons. The pathogen survives in infected seeds, plant residues (straw and stubble), but also in soil, water or weeds when environmental conditions are favorable. Helvolic acid and cerulenin are described as the major secondary metabolites of *S. oryzae* and the pathogenicity determinant of the disease. Temperature of 20-30 °C and relative humidity of 65-85% favour the sheath rot development.

Sheath rot in rice has also been associated with *Fusarium* sp. belonging to the *F. fujikuroi* complex. The complex is currently divided in three large clades, the African clade, the Asian clade and the American clade. The main organisms associated with rice are *F. verticillioides* from the African clade and the closely related species *F. proliferatum* and *F. fujikuroi* from the Asian clade. Symptoms of rice sheath rot caused by any of the members of the *F. fujikuroi* species complex are wide spread due to their large variability and at least one of their members is found in any part of the rice- growing world. Two categories of metabolites are involved in pathogenicity and interaction with plants, gibberellins and mycotoxins. *F. fujikuroi* can survive up to 26 months in infected rice grains and 28 months in dried rice stubble. *F. proliferatum* can survive in infected grains. Rice sheath rot causing *Fusarium* spp. have many hosts, they can easily find alternate hosts in the environment, especially weeds.

5.5. False smut

Rice false smut caused by the fungal pathogen *Ustilaginoidea virens* (Uv) is becoming a destructive disease throughout major rice-growing country. Information about genetic diversity and population structure of the pathogen is essential for rice breeding and efficient control of the disease. Recent reports applying genomic and transcriptomic data have revealed single nucleotide polymorphism (SNP) and simple sequence repeat (SSR) markers for the identification of Uv genetic diversity (Sun et al. 2013). Earlier studies using PCR-based approaches, such as rDNA-ITS variability amplified fragment length polymorphism (AFLP) and random amplification of polymorphic DNA (RAPD), have identified very limited genetic diversity of Uv.

However, three SNP-rich genomic regions have been identified by comparative genomics. Based on the analysis of the three SNP-rich genomic regions, significant genetic diversifications were detected among populations from five major rice production areas in China, and isolates from the same area showed considerable DNA composition stability, which consistent with the conjecture that Uv may not be an air-borne, but a water- and/or soil-borne pathogen. Consistent with this speculation geography is more important than rice cultivar in constructing the genetic diversity of Uv. Interestingly, genetic divergence is generally higher in isolates from inland areas than from coastal areas. Genetic variation in north-east China is relatively low, which may be a result of less active sexual reproduction. Survey of literatures reveals that except Baite et al (2014) who reported that the genetic variability of Indian isolates was related to geographical location as isolates from distantly related locations possess higher genetic diversity; there is no other reports on population structure of UV which is a good researchable issue that may be taken up in future.

5.6. Bakanae

In India, bakanae disease is also called as foolish seedling or foot rot because of the variable symptoms, the pathogen produces. The disease is monocyclic with pathogen producing conidia on infected plants and conidia will spread by wind and water. The high production of conidia on infected or dead culms in the field coincides with flowering and ripening of rice, when the conidia are able to infect or contaminate the seeds (Infected kernels develop a reddish color due to the presence of conidia, and the whole seed becomes discolored when severely infected). The fungus can also be isolated from asymptomatic seeds, if they are collected from a highly infected rice field. Airborne ascospores have also been reported, as an infection source, at the flowering stage of the crop. The fungus can infect seedlings at an early stage of development, when it becomes systemic in the plant, but without any colonization of the floral organs. The first 72 hours after seed germination are critical for the development of the disease, which is favoured by high amounts of exudates (sugars and amino acids) from germinating seeds.*F. fujikuroi* growth is also stimulated by temperatures from 27 °C to 30 °C, and by higher levels of nitrogen in the soil.

Soil temperature also plays a crucial role in disease development, with more prominent bakanae symptoms at 35 °C soil temperature. The application of nitrogen to the soil stimulated the development of the disease and the effect was not modified by the application of potassium or phosphorous. Relative humidity also plays an important role in disease development with high humidity leads to elongation of the culms, while low humidity causes rice plant stunting (Matic et al. 2016). Microconidia and mycelia of the pathogen develop in vascular bundles, particularly in larger vessels and in the xylem gaps, while the phloem and parenchyma do not seem to be infected. The fungus overwinters in infected seeds, and these represent the main source of inoculum for the following season. Progress in molecular taxonomy has shown that there are around 50 species in the *F. fujikuroi* complex and the number keeps increasing. The complex is currently divided in three large clades, the African clade, the Asian clade and the American clade. The main organisms associated with rice are *F. verticillioides* from the African clade and the related species *F. proliferatum* and *F. fujikuroi* from the Asian clade.

6. EPIDEMIOLOGY

6.1. False smut

Epidemiological study of false smut pathogen is essential to gather information for formulating appropriate management options. Till date there is no definitive pattern of infection process, dissemination method and the influence of weather factor vis-à-vis combination factors responsible for severe infection of false smut pathogen to rice. Nessa et al. (2015) provided a broad but relatively clear picture of on the epidemiology of rice false smut disease under natural environment and reported that soil is the source of initiation of epidemic but did not recognize any long or short distance primary or secondary source of infection. At Temperature 22-25 °C with no less than 48 h of wetness duration considered necessary for successful infection of sexual stage of FS pathogen *Villosiclava virens* and the highest level of disease (92.9%) was obtained at 25 °C and 95% RH with 120 h wetness. Light can inhibit the formation of secondary spores from chlamydospores. High level of nitrogen fertilization increases rice foliar growth which allowed for higher humidity below the canopy and created an environment favourable for the development of RFS. Additionally, irrigation has been found to be a major factor which affects the development of RFS. Lower minimum and maximum temperature, high atmospheric humidity (92% and above) before and during early part and less during later part of flowering favoured the disease.

7. DIAGNOSTIC ASSAY

7.1. Rice blast

Highly sensitive and accurate methods for the early diagnosis of *M. oryzae* will reduce quantum of loss. Traditionally, the major technique used to detect plant pathogens is based on cultural and morphological observation. Consecutively, some immunoassays and nucleic acid-based techniques have been developed for the diagnoses of plant pathogens. The enzyme-linked immunosorbent assay is a sensitive and specific method for the detection of plant pathogenic fungi. The most important is the polymerase chain reaction (PCR) based detection methods that are more accurate, sensitive and specific for diagnosis of blast disease. The quantification of M. oryzae growth in rice plant was developed based on RNA-based northern blotting and DNA-based real-time PCR.

7.2. Storage pathogen

Rice suffers from more than 60 diseases and most of the major diseases of rice are seed borne. Fungi are the principal organisms associated with seed storage (Fakir 2000). Bacteria are also commonly carried internally or externally by the seeds. The extremely seed borne diseases of rice are brown spot , bakanae , blast , sheath blight, sheath rot , stem rot , false smut are major seed borne pathogens of rice. Bacterial pathogens such as bacterial leaf blight and bacterial leaf streak are also taking a heavy toll in terms of yield and quality by rapid spread and damage. Seed may be infested, contaminated or infected. Seed infection may take place through the mother plant, invasion through natural openings including the funicles and microphyles, direct penetration of the seed or caryopsis or invasion from the pods or fruits.

Conventional detection and diagnosis methods coupled with molecular techniques can add to the rapid and accurate diagnosis. In rice, a BIOPCR technique was used to study survival of *Xanthomonas oryzae* pv. *oryza* in rice seed and track its progress in planta following seed transmission. Quantitative real time PCR detection will definitely help to quantify the pathogen load at an early stage so that further losses can be minimized. Loop-mediated isothermal amplification (LAMP) offers as a field oriented and user-friendly alternative to polymerase chain reaction (PCR). LAMP is less time intensive than PCR and can be performed using heat-blocks, with results read by eye under UV light.

8. KNOWLEDGE GAPS AND RESEARCH AND DEVELOPMENT NEEDS

The biotic stresses are major contributors to reduction of crop yield. Increasing ozone, CO_2 and greenhouse gases in the farming atmosphere are possible reasons for increasing pest pressure and change in pest species to rice crop. Scientific tools and techniques would ease the stresses endured by pest and diseases and shall provide better initiatives amongst entrepreneurial initiative.

Biotic menaces are weather-dependent, weather-based prediction models could be developed to manage these menaces. Forewarning models for major pests of rice using satellite-based agromet product and surface data could be developed for decision support system(s), which would reduce use of chemical pesticide on standing crop. Besides, the measurement of insect developmental, survival and reproductive responses to temperature poses practical challenges because of their modality, variability among individuals and high mortality near the lower and upper threshold temperatures. It will aid in the development of powerful tools for analyzing insect population behaviour and response to challenging climatic conditions. It is important to quantify and verify by critical experiments, the speculative relationships frequently proposed between climatic factors and the population dynamics of rice insects. Future experiments with population in controlled environments as well as statistical correlations based on field data will permit a much clear understanding of the importance of climate, and reveal the potential for improving pest control methodology through this understanding

9. WAY FORWARD

With the available scientific knowledge, there is need for further strengthening the research and development in the following areas:

- How temperature and other abiotic factors set the limits of distribution and define abundance of insect species.
- The physical and biological components of our environment are all interrelated. Thus, the rice fields need to be given the attention they need and deserve. Preventing alien species from invading the rice ecosystem is very important. Alien species often affect the conservation of endangered species by competition and inducing additional chemical control applications.
- The importance and abundance of natural enemies have not previously been investigated in different rice ecologies like upland, lowland, irrigated and deep water. The current work will address the paucity of information on enemies of paddy pests thriving in different rice ecologies and to have their comparative diversity.
- Issues and problems about rice fields should be taught in schools. Students should understand what is happening to a vital ecosystem such as rice fields so that they could make a stand and help preserve an important part of our environment and economy. Rice fields offer many benefits for all of us, like better rice and more food and better environmental safety.

10. CONCLUSION

The success of rice disease and pest management involves the understanding of various aspects of rice insect pests, pathogens, their pest status, distribution, bio-ecology, diversity, forecasting model for real-time pest-advisory services, hyper-spectral remote sensing in pest damage assessment, impact of climate change on insect biology, population structure and epidemiology of different rice pathogens. These knowledge will reduce chemical pesticide application in rice, financial burden and ultimately reduce environmental pollution.

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