e-Book

Adaptation Strategies for Pest Management in Climate Change Scenarios

Edited by

M Srinivasa Rao, TV Prasad, N Balasubramani, VK Singh

Organized by

ICAR Central Research Institute for Dryland Agriculture (CRIDA)
National Institute of Agriculture Extension Management (MANAGE)

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This e-book is a compilation of information with enriched research experience obtained from various subject experts for the Collaborative Online Training Programme of ICAR-CRIDA & MANAGE, Hyderabad on Adaptation Strategies for Pest Management in Climate Change Scenarios held during 17-19 February, 2022. This e-book has good information which is useful to the Extension personnel of Agri-allied sector, Faculty and students of Agricultural Universities, Subject Matter Specialists of KVKs, and extension functionaries of NGOs etc. Neither the publisher nor the contributors, authors and editors assume any liability for any damage or injury to persons or property from any use of methods, instructions, or ideas contained in the e-book. No part of this publication may be reproduced or transmitted without prior permission of the publisher/editor/authors. Publisher and editor do not give warranty for any error or omissions regarding the materials in this e-book.

Published for Dr. P. Chandra Shekara, Director General, National Institute of Agricultural Extension Management (MANAGE), Hyderabad, India by Dr. Srinivasacharyulu Attaluri, Program Officer, MANAGE and printed at MANAGE, Hyderabad as e-publication.

Foreword

National Institute of Agricultural Extension Management (MANAGE), Hyderabad is an autonomous organization under the Ministry of Agriculture & Farmers Welfare, Government of India. The policies of liberalization and globalization of the economy and the level of agricultural technology becoming more sophisticated and complex, calls for major initiatives towards reorientation and modernization of the agricultural extension system. Effective ways of managing the extension system needed to be evolved and extension organizations enabled to transform the existing set up through professional guidance and training of critical manpower. MANAGE is the response to this imperative need. Agricultural extension to be effective, demands sound technological knowledge to the extension functionaries and therefore MANAGE has focused on training program on technological aspect in collaboration with ICAR institutions and state agriculture/veterinary universities, having expertise and facilities to organize technical training program for extension functionaries of state department.

Climate change is the current burning issue which have a major impact on crop production and agricultural pests. Insect pests respond differently to different causes of climate change which affects pest's reproduction, survival, spread and population dynamics as well as the relationships between pests, the environment, and natural enemies. Climate change creates new ecological niches that provide opportunities for insect pests to establish and spread in new geographic regions and shift from one region to another. Farmers can expect to face new and intense pest problems in the coming years due to the changing climate. The spread of crop pests across physical and political boundaries threatens food security and is a national problem. Therefore, understanding of adaptation strategies for pest management in the context of climate change scenarios is required in minimizing the economic losses caused by the pests to achieve the higher productivity.

It is a pleasure to note that, ICAR-Central Research Institute for Dryland Agriculture, (CRIDA), Santoshnagar, Hyderabad and MANAGE, Hyderabad, Telangana is organizing a collaborative training program on *"Adaptation Strategies for Pest Management in Climate Change Scenarios"* and coming up with a joint publication as ***e-book*** as immediate outcome of the training program.

I wish the program be very purposeful and meaningful to the participants and also the e-book will be useful for stakeholders across the country. I extend my best wishes for success of the program and also, I wish ICAR-Central Research Institute for Dryland Agriculture (CRIDA), Santoshnagar, Hyderabad many more glorious years in service of Indian agriculture and allied sector ultimately benefitting the dryland farmers. I would like to compliment the efforts of Dr. N. Balasubramani, Director (Climate Change and Adaptation), MANAGE, Hyderabad, Dr. M. Srinivas Rao, Principal Scientist (Entomology) and Dr. T.V. Prasad, Principal Scientist, (Entomology), Division of Crop Sciences, ICAR-CRIDA for this valuable publication.

Dr. P. Chandra Shekara
Director General,
MANAGE

Foreword

ICAR-Central Research Institute for Dryland Agriculture (CRIDA) is a premier research institute in the field of Natural Resource Management for Dryland Agriculture in India under the Ministry of Agriculture and Farmers Welfare, New Delhi. ICAR-CRIDA is working closely with different stakeholders (farmers, line department officials, SAUs, other ICAR institutes, different ministries, etc) towards the development of climate resilient agriculture in India apart from production enhancement and revenue generation through introduction of easily adaptable cost-effective advance technologies in a sustainable ecosystem based approach.

ICAR-CRIDA is currently implementing the ICAR flagship programme, National Innovations on Climate Resilient Agriculture (NICRA), which is playing an important role at national level in evolving adaptation and mitigation strategies in agriculture and allied sectors and also taking up their demonstration in more than 150 villages representing key climate vulnerabilities. The effects of climate change on incidence of insect pests and diseases is an important dimension of overall impact on agriculture. Understanding of the complex, spatially variable and species-specific effects of climate change is essential to develop an appropriate pest management option. This requires building the capacity of researchers and other stake-holders in the country.

Keeping this in view, ICAR-CRIDA & MANAGE together are organizing a collaborative online training program on *"Adaptation Strategies for Pest Management in Climate Change Scenarios"* for the extension functionaries of agri-allied sector, faculty and students of agricultural universities, KVK-SMS, NGOs extension functionaries etc., I hope this training programme will sensitize different officials involved in extension activities about the impacts of Climate Change on pests and improve the preparedness of the farmers in fine tuning IPM strategies for protecing the crops from the losess caused by the major pests in different crops.

Lectures delivered by the interdisciplinary group of experts from entomology, plant pathology, social, and allied subjects are captured and prepared as this ***e-book***. It contains important topics on impact of climate change scenarios on the dynamics of insect pests of national importance and new researchable areas on impact of climate change on the biological control agents and other natural enemies. The book also covers topics about ecofriendly and easily adaptable technologies on the ground level by creating better awareness among the farmers. Hope wide circulation of this book will help a large number of readers to enrich their knowledge on adaptation strategies for pest management in the context of climate change scenario in India.

February, 2022

Vinod Kumar Singh
Director, ICAR-CRIDA

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Impact of Climate Change on Indian Agriculture

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Indian Agriculture is highly vulnerable to climate change with 51% cultivated area under rainfed conditions. One or other part of the country is experiencing frequent extreme weather events causing sizeable loss to yield and income to the farmers at micro scale and to the Nation's economy at macroeconomic level. As per the latest IPCC AR-6 Report increase in rainfall, high inter annual variability, intense and frequent heatwaves, likely temperature increase by 1.5 to 4.0^{o}C and rise in sea level by 300 mm could be the major challenge for sustainable agriculture in the coming years. This necessitates accelerated research on for developing resilient technologies against climate change as well as their mainstreaming through the adaptation mechanism for upscaling. Therefore, Government of India has accorded high priority on research and development to cope with climate change in general and agriculture in particular. The Prime Ministers National Action Plan on Climate Change has identified Agriculture as one of the 8 National Missions. To meet the challenges of sustaining domestic food production in the face of changing climate and to generate information on adaptation and mitigation in agriculture to contribute to global fora like UNFCCC, ICAR, Ministry of Agriculture and Farmers Welfare, Government of India launched a flagship project National Innovations in Climate Resilient Agriculture (NICRA) in February 2011.

NICRA is the unique project which brings all sectors of agriculture viz., crops, horticulture, livestock, fisheries, natural resource management (NRM) and extension scientists on one platform. The project is initiated to develop and promote climate resilient technologies in agriculture which will address vulnerable areas of the country and outputs of the project will help the districts and regions prone to extreme weather conditions like droughts, floods, frost, heat waves, etc. to cope with such extremes. The project is implemented through components viz. strategic research, technology demonstration and capacity building in 151 clusters of villages in each one of the identified climatically vulnerable districts to demonstrate proven technologies and enhance adaptive capacity of farmers. This network project is operated with the objectives: (i) to undertake strategic and applied research on climate change adaptation and mitigation (ii) to validate, demonstrate and assess the impact of climate resilient technologies on farmers' fields (iii) to strengthen the capacity of scientists, farmers and other stakeholders on climate resilient agriculture.

In the strategic research component, both short term and long-term research programs with a national perspective have been taken up to evolve adaptation and mitigation strategies in crops, horticulture, natural resources, livestock, fisheries and poultry. The main thrust areas covered are (i) identifying most vulnerable districts/regions, (ii) evolving crop varieties and management practices for adaptation and mitigation, (iii) assessing climate change impacts on livestock, fisheries and poultry and identifying adaptation strategies. About 57 ICAR Institutes, 16 State Agriculture Universities, Indian Institute of Technology (Chennai), NGOs are involved in strategic research. The State of art research infrastructure was developed like high throughput phenotyping platforms, free air temperature elevation systems in open fields, carbon dioxide temperature gradient chambers, environmental growth chambers with CO_2 and temperature controls and special calorimetric system to study livestock response to heat stress.

The impacts of climate change on production of major crops (rice, wheat, maize, onion), soil organic carbon, livestock and fish species were studied through integrated simulation modelling framework to rising temperatures and carbon-dioxide. In the absence of adoption of adaptation measures rainfed rice yields in India are projected to reduce by 20% in 2050 and 47% in 2080 scenarios while, irrigated rice yields are projected to reduce by 3.5% in 2050 and 5% in 2080 scenarios. Climate change is projected to reduce wheat yield by 19.3% in 2050 and 40% in 2080 scenarios towards the end of the century with significant spatio-temporal variations. Climate change is projected to reduce the *kharif* maize yields by 18 to 23% in 2050 and 2080 scenarios. However, adopting improved varieties coupled with improved agronomic management can improve the rice yields by 17% in irrigated condition and by about 35% in rainfed condition, wheat yields by about 40%, maize yields by about 10%. *Kharif* groundnut yields are projected to be increased by 7% in 2050 scenario where as in 2080 scenario the yield is likely to decline by 5%. Future climates are likely to benefit chickpea with increase in productivity. Climate-induced pest and disease outbreaks in the country were studied in 9 crops viz., rice, wheat, sorghum, chickpea, mustard, safflower, potato, tomato and onion (10 insects and 29 diseases) to build pest and disease forewarning models. Web enabled and mobile apps for pest forewarning (6 crops), App for Forewarning Blue Tongue Disease in cattle have been developed and made available to farmers.

Technology Demonstration is a participatory program of NICRA involving farmers with the objectives viz., to demonstrate site-specific technology interventions on farmers' fields for coping with climate variability in climatically vulnerable districts, to generate awareness and build capacity of farmers and other stakeholders on climate resilient agriculture and to evolve innovative institutional mechanisms at village level that enable the communities to respond to climate stresses in a continuous manner beyond the project period. The technology demonstrations aim at taking the resilient technologies to the farmers' door steps for reducing the vulnerability and enhancing the adaptive capacity of farming community at village level and develop climate resilient model villages to upscale further. One village or a cluster of villages from each of the 151 selected districts were selected for this purpose. In view of the frequent weather aberrations around the year in one or other part of the year impacting agricultural production, to minimize the losses in agriculture, to improve the efficiency of the production systems and to enhance the production and income, the need was felt to implement contingency measures on real-time basis. Thus, RTCP was conceptualized under technology demonstration of NICRA by AICRPDA and implemented in NICRA villages.

The interventions are broadly divided into four modules viz., natural resource management, crop production, livestock and fisheries and creation of institutional structures for sustaining the activities envisaged and scaling up of interventions. NRM interventions included *in-situ* moisture conservation, residue incorporation instead of burning, green manuring, water harvesting and efficient use, zero tillage, artificial ground water recharge, water saving irrigation methods etc. Under the crop production module, demonstrations consist of drought/ temperature tolerant varieties, advancement of planting dates of *rabi* crops, water saving paddy cultivation methods *viz.* SRI, aerobic and direct seeding, frost management in horticulture through fumigation and location specific intercropping systems etc. Under the livestock & fishery module demonstrations on use of community lands for fodder production during droughts/floods, augmentation of fodder production through improved planting material, improved fodder/feed storage methods, fodder enrichment, prophylaxis, improved shelters for reducing heat stress in livestock, management of fish ponds/tanks during water scarcity are being taken up. Village level institutional mechanisms such as Village Level Climate Risk Management Committees (VCRMC), custom hiring centers are created for managing infrastructure created and to improve the timeliness of operations during the limited window periods of moisture availability in rainfed areas and to promote small farm mechanization for adoption of climate resilient practices. These interventions helped farmers to reduce the yield losses and enhanced their adaptive capacity against climatic variability.

A large-scale capacity building program on climate resilient agriculture is being undertaken with more than 1200 scientists, 872 research scholars and 160 of doctoral and post graduate students are involved on climate change research and dissemination of climate resilient technology across the country. These resilient practices are being adopted by communities and spreading beyond NICRA villages. In the past decade years 16,958 capacity building programs were conducted throughout the country under NICRA project to educate stakeholders on various aspects of climate change and resilient technologies, covering 5,14,816 stakeholders so as to enable wider adoption of climate resilient technologies and increase in yields. The NICRA project initiated a decade ago will continue to operate with enhanced scope and emerging challenges.

Climate Change Impact on Crop-Pest Interactions and Pest Management Adaptations thereof

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Climate is an important determinant of the abundance and distribution of biological species. Over past hundred years, the global temperature has increased by 0.8 °C and is expected to reach 1.1-5.4 °C by the end of next century. On the other hand, CO_2 concentration in the atmosphere has increased drastically from 280 to 370 ppm and is likely to be doubled in 2100 (IPCC, 2007). Change in the global climate may affect the crop yields, incidence of pests and economic costs of agricultural production. Climate change is expected to have significant impacts on the distribution, phenology and abundance of many species over the next few decades. The climate change impacts on insects may include shifts in species distributions with shift in geographic ranges to higher latitudes and elevations, changes in phenology with life cycles beginning earlier in spring and continuing later in autumn, increase in population growth rates and number of generations, change in migratory behaviour, alteration in crop-pest synchrony and natural enemy-pest interaction, and changes in interspecific interactions (Sutherst, 1991; Root *et al.*, 2003). Extreme weather events such as intense rainstorms, wind or high temperatures also affect survival of insect populations. For species to survive changing climates, they must either adapt *in situ* to new conditions or shift their distributions in pursuit of more favourable ones. Changes in rainfall pattern also have implications for insect survival. It is being predicted that frequency of rainfall would decrease, but its intensity would increase. This may lead to floods on one hand and long dry spells on the other. More intense rainfall as project under climate change may thus reduce incidence of small pests on crops. Aphid population on barley was negatively related to January mean minimum temperature and February total rainfall (Chander *et al.*, 2003).

Pest management has potential to provide eco-friendly sustainable solution to obnoxious pest problems. However, the relative efficacy of pest management components such as, host-plant resistance, bio-pesticides, natural enemies and synthetic chemicals is liable to change as a result of global warming. It therefore becomes important to assess climate change impact on insect populations and adopt suitable pest management adaptations for their effective management.

Climate change impacts on crop pests

Climate change will have both direct as well as indirect effects on insect populations. Temperature is the major factor in global climate change that directly affects insect development, reproduction and survival. Although insect responses to global climate change will vary, the effect of global warming in general has been predicted to increase intensity of herbivore pressure on plants. Climate change will also affect insects indirectly through their host plants.

Direct effects of climate change on insects

Expansion of habitat range: Any increase in temperature is bound to influence the distribution of insect populations. Species might expand into regions that become favourable as a result of climate change and withdraw from regions that cease to be favourable. Climatic warming will thus allow the majority of temperate insect species to extend their ranges to higher latitudes and altitudes. Insects being the cold-blooded, temperature is the most important environmental factor influencing their behaviour, distribution, development, survival, and reproduction. It is predicted that 1^{o}C temperature increase would extend distribution of species 200 km northwards or 140 m upwards in altitude (Parry and Carter, 1989). There is a need to regularly observe activity of pests in different regions in terms of timing, population size and habitat ranges for drawing any meaningful conclusions.

Changes in over-wintering success: With rise in temperature, onset of hibernation may be delayed, while it may be suspended earlier than usual in spring thereby increasing period of activity of pests. The pests can therefore colonize crops more quickly during spring and earlier pest flights are known to occur after milder winters.

Change in migrating behaviour: Minimum temperature plays important role in determining the global distribution of insect species rather than maximum temperature. Hence any increase in temperature will result in greater ability of insects to over-winter at higher latitudes. The global warming may affect thus migration and extend distribution of the pest further north.

Changes in interspecific interactions: The effect of climate change on species distribution and abundance could involve not only direct effect on each species individually in an ecosystem but it may also influence interspecific interactions. Rapeseed-mustard is infested by two aphid species, *Lipaphis erysimi* and *Myzus persicae*, the former being dominant during severe winters while the latter during mild winters (Chander and Phadke, 1994). With rise in temperature, higher incidence of *Myzus persicae* may be witnessed. Such faunal shifts may also take place in other crops. Likewise, pest-natural enemy interactions are also subject to influence of climate change.

Changes in population growth rates: Warming would affect temperate annual and multivoltine species in different ways and to different degrees. In case of multivoltine species such as aphids and some lepidopterans, higher temperatures would allow faster development rate probably allowing for additional generations within a year (Pollard and Yates, 1993). It has been observed that tropical insects are relatively sensitive to temperature changes and are currently living very close to their optimum temperature (Deutsch et al., 2008). This implies that with 2-3 ^{o}C temperature rise, ambient temperature may exceed the upper limit of favourable temperature range, thereby adversely affecting growth and development of pests.

Indirect effect through host plants

Effect of increased CO_2**:** The elevated CO_2 induces increased plant size and canopy density with high nutritional quality foliage and microclimate more conducive to pests. Under higher CO_2, there is an increase in C:N ratio of plant foliage that increases feeding of herbivores in order to derive more amino acids. Rao et al. (2014) observed a higher relative proportion of carbon to nitrogen (C:N) in peanut foliage grown under elevated CO_2 than ambient CO_2 and reported that the pest incidence was likely to be higher in the future. Elevated CO_2 had a positive effect on BPH multiplication that resulted in more than doubling of its population compared to ambient $CO_{2.}$ Besides, honey dew excretion was also more under elevated CO_2 (Prasannakumar *et al*., 2012).

Effect of increased temperature: Climate change may alter the interactions between the insect pests and their host plants (Sharma *et al*., 2010). Elevated temperature may cause breakdown of temperature sensitive resistance to certain insect pests.

Assessment of impact of climate change on pest species

Impact of global climate change on crop productivity and pest population can be assessed through experiments as well as through crop growth and insect population models.

Experimental approach

Direct impact of temperature: Probable impact of temperature rise on insect populations can be known by comparing current and projected temperature conditions at a location with a species' favourable temperature range. Favourable temperature range for a species can be established by rearing it at a series of low to high constant temperatures in BOD incubators or growth chambers. Fecundity, hatching, development period, weight, survival and adult emergence should be recorded at as small intervals as possible to account for small differences in development period at different temperatures. Data on temperature dependent development period and survival can then be used to determine favorable temperature range and computing thermal constant and development thresholds for the species (Sujithra and Chander, 2013; Selvaraj and Chander, 2015).

Indirect impact of CO_2: Impact of CO_2 on insect population via host plants can be studied through open top chambers (OTCs) and free air carbon dioxide enrichment (FACE). Prasannakumar *et al*., (2012) studied effect of elevated CO_2 on BPH population in OTCs. It was observed that despite nutritive effect of elevated CO_2 on rice crop, BPH induced losses were more under it owing to higher pest population as well as sucking rate.

Effect of rainfall: Distribution and frequency of rainfall may also affect the incidence of pests directly as well as through changes in humidity levels. It is being predicted that under climate change, frequency of rainfall would decline, while its intensity would increase. Under such situation, incidence of small pests such as aphids, jassids, whiteflies, mites on crops may be reduced as these get washed away by heavy rains. Aphid population on wheat and other crops was adversely affected by rainfall and sprinkler irrigation (Chander, 1998).

Modelling approaches

Climate Matching: Climate matching involves the computation of a “match index” to quantify the similarity in climate between two or more locations. The match index is based on variables such as monthly minimum and maximum temperatures, precipitation, and evaporation. Software packages for climate matching include BIOCLIM (Busby, 1991), and CLIMEX (Sutherst and Maywald, 1985). Climate matching may be used for climate change impact assessment by identifying those locations on the globe, where current climate is most similar to the predicted future climate at the location of interest.

Empirical Models: Empirical models based on long-term data on pest incidence and weather variables can be used to assess the likely impact of climate change on pest status in a region. Chander *et al*. (2003) related aphid incidence on barley crop variety ‘DL-70’ during *rabi* season from 1985-86 to 1999-2000 to weather parameters and found an appreciable inter annual variation in aphid incidence probably due to climatic variability. The aphid population on barley exhibited a declining trend with time and it had a negative relationship with January mean minimum temperature and February total rainfall.

Simulation Models: Simulation models have been used widely to assess climate change impact on yield of various crops in different agro ecological zones. However, biotic stresses like insects, pathogens, and weeds have largely been ignored in these studies. This requires that emphasis be laid on population dynamic simulation and their coupling with crop growth simulation models.

Insect population simulation model can be developed based on various bio-ecological factors of a species viz., fecundity, sex ratio, migration, abiotic and biotic mortality factors, development thresholds and thermal constants (Reji and Chander, 2008; Sujithra and Chander, 2013; Selvaraj and Chander, 2015). Population simulation model can be coupled to crop growth model at relevant plant processes depending on pest damage mechanisms. Crop-pest model can then be used to analyze impact of climate change on insect dynamics as well as crop-pest interactions.

Mitigation of climate change

Mitigation is the adoption of measures against sources of greenhouse gases to reduce their emission. For climate change mitigation, fossil fuel use in pest management related activities should be reduced. Pesticides manufacturing, transportation and power spraying requires a lot of energy and by curtailing pesticide consumption, green house gas emission can be reduced. Pest management can play important role in mitigation of global climate change as it stresses on judicious use of agricultural inputs such as fertilizers and pesticides. Transplanted rice is one of the major sources of methane from agriculture along with dairy cattle. Continuous flooding of rice fields leads to emission of methane, an important green house gas and it also aggravates problem of plant hoppers on the crop. Likewise, excess use of nitrogenous fertilizers stimulates pests' population and is also responsible for nitrous oxide emission. Therefore, alternate wetting and drying as emphasized in pest management, mitigates methane emission and also reduces plant hopper incidence on the crop.

Adaptation to climate change

Pest management components such as host-plant resistance, bio-pesticides, natural enemies, and synthetic chemicals are exploited for management of pests. However, the relative efficacy of many of these pest control measures is likely to change as a result of global warming. Climate change could affect efficacy of crop protection chemicals through (a) changes in temperature and rainfall pattern, and (b) morphological and physiological changes in crop plants (Coakley *et al.,* 1999). To sustain agricultural productivity under climate change, pest management adaptations assume significance to ensure effectiveness of management tactics against pests.

Pest surveillance

Monitoring: Monitoring is the backbone of the IPM. The most important aspect of monitoring that needs to be fully exploited keeping in view the climate change scenario is detection of invasive species. The known ecological impacts of invasive species include loss of threatened and endangered species, altered structure and composition of terrestrial and aquatic communities, and reduction in overall species diversity.

Detection of changes in insect distribution: Climate change is expected to have significant impact on insect distribution and it thus becomes important to detect potential change in ranges of species distribution for their effective management. Generic modelling tools such as BioSim and CLIMEX have proved useful in such studies. BioSim uses available knowledge about the responses of particular species to key climatic factors to predict their potential geographic range and performance (Régnière and St-Amant, 2008).

***Pest forewarning*:,**Reliable medium-range weather forecast can help in proper timing of crop management practices such as sowing, irrigation, fertilizer application and pesticide application. This would increase efficiency of crop production and protection technology. Likewise, pest forecasting can help in cautioning farmers about impending pest situation and adoption of preventive measures to avert pest problems.

Pest Management Components

Host-plant resistance, biological control, cultural control and chemical control are the major pillars of the IPM. These components are likely to be affected by climatic change and thus would need appropriate modifications for sustaining their effectiveness.

***Host plant resistance*:** Breakdown of temperature-sensitive resistance under increased temperature regimes may lead to more rapid evolution of pest biotypes. Sorghum varieties that were resistant to sorghum midge, *Stenodiplosis sorghicola* (Coq.) in India became susceptible to the pest under high humidity and moderate temperatures in Africa (Sharma *et al*., 1999). With global warming and increased water stress, tropical countries like India might face the problem of higher yield losses in sorghum due to breakdown of resistance against the midge and spotted stem borer *Chilo partellus* Swinhoe.

***Biological control*:** Biodiversity is very important for abundance of insect pests and their natural enemies. It thus calls for increasing functional diversity in agro-ecosystems that are prone to climate change so as to improve their resilience and reduced pest induced yield losses. Hosts might pass through vulnerable life stages faster at higher temperatures, reducing the time available for parasitism, thereby giving a setback to the survival and multiplication of parasitoids (Gutierrez, 2008). There is thus a need to breed temperature-tolerant natural enemies of pests. Increase in time of herbivore development due to changes in plant nutrition can make herbivore prey more susceptible to predation because of the ample opportunity available to predators. Fungi such as *Metarhizium anisopliae, Beauveria bassiana*, *Baculovirus,* nuclear polyhedrosis virus (NPV), cytoplasmic virus and bacteria like *Bt* have great potential for development as microbial control agents. Because of their selectivity and minimal environmental impact, microbial control agents will be ideal components of integrated pest management programmes under climate change.

***Cultural control*:** Global climate change would cause alteration in sowing dates of crops, which may alter host-pest synchrony. There is need to explore changes in pest-host interaction under agronomic management adaptations. *Helicoverpa armigera* and *Bemisia* *tabaci* are late season pests of cotton and by sowing till mid-May, crop can escape damage from these pests. Early sowing can be used to minimize pod borer, *H. armigera* damage to chickpea in North India, BPH damage in rice, and mustard aphid damage in *Brassica* crops.

Chemical control: Climate change could affect efficacy of crop protection chemicals through (a) changes in temperature and rainfall pattern, and (b) morphological and physiological changes in crop plants (Coakley *et al.,* 1999). An increase in probability of intense rainfall could result in increased pesticide wash-off and reduced pest control. In contrast, increased metabolic rate at higher temperature could result in faster uptake by plants and higher toxicity to pests. Likewise, increased thickness of epicuticular wax layer under high CO_2 could result in slower or reduced uptake by host, while increased canopy size may hinder proper spray coverage and lead to a dilution of the active ingredient in the host tissue. The rates of pesticide application thus have to be modified according to new situations. Granular formulations may prove more effective as these are less liable to be washed by rainfall.

Reliable medium-range weather forecast can help in predicting rainfall and avoid pesticide application under imminent rainy conditions. Likewise, regular monitoring can help in undertaking control interventions at right time, thereby helping in managing small population levels easily and effectively. Properly timed pesticide application, application coinciding with egg hatching, proves more effective than many ill-timed applications. Likewise, proper placement of pesticide is also equally important to ensure its efficacy against pests. In case of rice planthoppers, pesticide application needs to be targeted at plant stems, because foliar spray on canopy proves of little or no use.

Conclusion

Climate change is imminent and it has started showing its effect on organisms and insects are no exception to it. Climate change will also impinge upon efficacy of pest management components. It thus becomes very important to assess climate change impact on insects and pest management components and adopt appropriate mitigation and adaptation measures to sustain agricultural productivity. Simulation models have been used for several applications in the area of pest management, which helped to increase the efficiency of field research greatly. These will be of even greater relevance in new emerging research areas such as climate change impacts on pests and crop yield, impacts of transgenics on environment, pest risk analysis for sanitary and phytosanitary requirements and pest forecasting.

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Application of Remote Sensing for Pest Damage Assessment

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Remote sensing is the science and art of obtaining information about an object, area, or phenomenon through the analysis of data acquired by a device that is not in contact with the object under investigation. When electromagnetic energy is incident on any feature on the earth surface, three energy reactions with the feature are possible: reflection, absorption and/or transmission (Lillesand et al., 2004). The portion of energy reflected, absorbed or transmitted will vary for different earth features depending on their material type and condition. Even within a given feature type, the portion of reflected, absorbed and transmitted energy will vary at different wavelengths. Thus, two features may be distinguishable in one spectral range and be very different in another wavelength band. Because many remote sensing systems operate in the wavelength regions in which reflected energy predominates, the reflectance properties of earth surface are very important. The reflectance characteristics of earth surface features may be quantified by measuring the portion of incident energy that is reflected (Panda 2005). Reflectance is measured as a function of wavelength and is called spectral reflectance. A graph of the spectral reflectance of an object as a function of wavelength is termed as 'spectral reflectance curve'.

Remote sensing platforms can be field-based (ground based), or mounted on aircraft (airborne) and satellites (space borne). Satellite RS is generally for large-scale study but it often cannot meet the requirement of spatial resolution in applications. Ground-based platform, such as hand-held spectroradiometer, is typically used for ground truth study. Airborne RS is flexible and able to achieve different spatial resolutions with different flight altitudes. Application of remote sensing for crop protection applications has considerable progress over the years (Prabhakar et al, 2012a). However, its use in India is limited owing to very few studies. The first successful application of remote sensing in India started with coconut wilt (Dakshinamurty, 1971). However, several workers have reported on its application for crop protection in different crops. Details are summarised below.

Potato:

Utility of ground-based hyperspectral data for detecting the potato late blight at early level of infestation was explored by Ray et al. (2011). The hyperspectral reflectance curves showed that healthy plants have high reflectance NIR region and low reflectance in red region. The highest differences from healthy plants were recorded at highest level of infestation of 98% and it decreased with decrease in infestation. Based on the overall accuracy and Kappa coefficient values the LSWI was found to be superior compared to NDWI. Therefore, the LSWI was used to estimate area damaged by thrips and their infestation levels from the satellite imagery. The results showed that the chilli area under healthy was reduced from 2244.6 ha to 840.6 ha over a period of one month (10th January and 9th February 2016), mostly due to thrip damage. Whereas, the chilli area under medium and severe thrip damage categories was found increased from 174.28 ha to 807.48 ha and 215.04 ha 786.16 ha, respectively.

Rice:

Prasannakumar et al. (2013) attempted to detect stress in rice plants grown in pots caused by the Brown Planthopper (BPH), *Nilaparvata lugens*. BPH damage influenced reflectance of rice plants compared to uninfected plants in the visible and near-infrared regions of the electromagnetic spectrum. Based on rice plant reflectance corresponding to the sensitive wavelengths, three hyperspectral indices were developed. A multilinear regression model was developed between BPH damage levels and plant reflectance. Severe incidence of brown plant hopper (BPH) in few villages of East Godavari (EG) district, Andhra Pradesh (A.P.) was identified through extensive field surveys (Prabhakar et al., 2013a). Ground based multispectral radiometric studies (CropScan16R) in rice showed spectral reflectance between 760-1100 nm could differentiate healthy and rice BPH infestation. Disease water stress index was found better than several other spectral vegetation indices for the early detection of rice BPH damage. IRS P6- LISS IV Mx satellite data was assessed to detect BPH damage in selected villages.

Cotton:

Capability of remote sensing techniques for detection of leafhopper (LH) severity stress on cotton was studied by Prabhakar et al (2011). Plotting linear intensity curves between reflectance at each waveband with infestation grade resulted in six sensitive bands that exhibited maximum correlation at different regions of the electromagnetic spectrum (376, 496, 691, 761, 1124 and 1457 nm). Regression analysis of several ratio indices formulated with two or more of these sensitive bands led to the identification of new leaf hopper indices (LHI) with a potential to detect leafhopper severity. These new indices along with 20 other stress related hyperspectral indices compiled from literature were further tested for their ability to detect LH severity. Two novel indices LHI 2 and LHI 4 proposed in this study showed significantly high coefficients of determination across locations (r^2 range 0.521 to 0.825) and have potential use for detection of leafhopper severity in cotton. Prabhakar et al. (2013b) characterized reflectance spectra of cotton plants with mealybug infestation and identified specific narrow wavelengths sensitive to damage. Reflectance measurements were made using a hyperspectral radiometer. Significant differences were found in green, near infrared and short wave infrared spectral regions for plants with early stages of *P. solenopsis* infestation, and for plants showing higher grades of infestation these differences extended to all the regions except blue. Reflectance sensitivity analysis of the hyperspectral data revealed wavelengths centered at 492, 550, 674, 768 and 1454 nm as most sensitive to mealybug damage. Mealybug Stress Indices (MSIs) were developed using two or three wavelengths, tested using multinomial logistic regression (MLR) analysis and compared with other indices published earlier. Results showed that the MSIs were superior ($r^2 = 0.82$) to all other spectral vegetation indices tested. The overall percent correct classification of cotton plants into different mealybug damage severity grades was in the range of 38.3 and 54.9. High classification accuracy for grade-1 (81.8%) showed that models are capable of early detection of mealybug damage.

Blackgram:

A rapid and non-destructive estimation of yellow mosaic disease (YMD) in black gram by hyperspectral remote sensing was developed (Prabhakar et al, 2013c). With optimal spectral reflectance ratios as inputs, disease prediction models were built using multinomial logistic regression (MLR) technique. Based on model fit statistics, reflectance ratios R571/R721 and R705/R593 were found better than the individual bands R571 and R705. The MLR model using R705/R593 as dependent variable was of greater accuracy as it gave lower values of standard errors for slopes and highly significant estimates of intercept and slope ($p < 0.05$). Thus, the models developed have potential use for rapid and non-destructive estimation of leaf chlorophyll and yellow mosaic disease severity in blackgram.

Sorghum:

Singh et al (2007) studies on crop sorghum that is a forage variety and the pest observed was a species of grasshopper. Linear regression analysis was carried out to obtain the best suitable incidence angle and polarization to assess the sorghum. A negative correlation has been obtained between TC and scattering coefficient with the r^2 values (0.69 and 0.75 for HH- and VV-pol, respectively). The TC assessed by the microwave measurements was helpful to estimate the occurrence of pests on sorghum. Based on both phase of study an algorithm is proposed to estimate the number of pests on sorghum by remote sensing method.

Prabhakar et al (2021) studied on fall armyworm (FAW) Damage on sorghum from the farmers' fields of southern India was assessed using space-borne data. Comparison of the Sentinel-2A satellite data of pre and post infestation periods revealed reduction in Leaf Area Index (LAI) in the infested fields. Groundtruth data confirmed that FAW infestation reduced LAI by 49.7%, biomass by 32.5% and grain yield by 51.8%. Infestation at Panicle Initiation (PI) stage caused maximum yield loss compared to flag leaf visible and boot stages. The interaction results showed FAW infestation at different crop stages had significant effect on biomass and yield, but not on LAI. Regression analysis with spectral vegetation indices revealed LAI (r^2: 0.82) and NDVI (r^2: 0.80) were significantly superior in identifying FAW infestation from the satellite data.

Mustard:

Space borne hyperspectral data from Hyperion was used to classify healthy and diseased mustard crop in Bharath region of Rajasthan (Datta et al. 2006). The absorption in red region at 681 nm decreased with disease intensity at 1660 nm the diseased crop showed sharp decease in reflectance. Similarly, difference in spectral profiles of different levels of disease score can be differentiated very well at 2000-2400 nm range. The highest difference in reflectance was found at 2143 nm. The stress detected by hyperspectral data is not due to water scarcity as the study area is fully irrigated. The Disease Water Stress Index (1660/680 nm) showed 68% correlation with disease score for the mustard crop. Using DWSI disease severity in mustard can be distinguished very well.

Chilli:

An attempt has been made to discriminate healthy and pest affected chilli crop in the multispectral satellite imagery using several multispectral spectral vegetation indices (Prabhakar et al., 2019). A total of 51 fields were surveyed in predominantly chilli growing mandals during the rabi season of 2015-2016 in Mahaboobnagar district, Telangana state. Sentinel 2A satellite data was used to calculate the spectral vegetation indices viz., Normalized Difference Vegetation Index (NDVI), Soil-adjusted Vegetation Index (SAVI), Land Surface Water Index (LSWI) and Normalized Difference Infrared Index (NDII) and Normalized Difference Water Index (NDWI). Values of LSWI in the range of 0.04 to 0.18 has been classified as severe, whereas values between 0.18 to 0.24 and 0.24 to 0.50 were classified as medium and healthy, respectively. Whereas the NDWI values between 0.5 to 0.72, 0.4 to 0.52 and 0.2 to 0.4 were categorized as healthy, moderate and severe classes. The producer's accuracy of LSWI classified image showed that chilli healthy, moderate and severe infestation were to be 98.78, 89.46 and 86.27 %, respectively, and users’ accuracy were found 55.39, 23.04 and 21.57 %, respectively. Based on the overall accuracy and Kappa coefficient values the LSWI was found to be superior compared to NDWI. Therefore, the LSWI was used to estimate area damaged by thrips and their infestation levels from the satellite imagery. The results showed that the chilli area under healthy was reduced from 2244.6 ha to 840.6 ha over a period of one month (10th January and 9th February 2016), mostly due to thrip damage. Whereas, the chilli area under medium and severe thrip damage categories was found increased from 174.28 ha to 807.48 ha and 215.04 ha 786.16 ha, respectively.

Soybean:

Gazala et al (2013) examines spectral reflectance of soybean leaves due to Mungbean yellow mosaic India virus (MYMIV) infection in order to identify YMD sensitive spectral reflectance. Spectral reflectance measurement indicated significant change in reflectance in the infected soybean canopy as compared to the healthy one. In the infected canopy, reflectance increased in visible region and decreased in near infra-red region of spectrum. Reflectance sensitivity analysis indicated wavelength 642nm, 686nm and 750 nm were sensitive to YMD infection. Whereas, in yellow leaves induced due to nitrogen deficiency, the sensitive wavelength was 589 nm. Due to viral infection, a shift occurred in red and infra-red slope on the left in comparison to healthy one. Red edge shift was a good indicator to discriminate yellow mosaic as chlorophyll gets degraded due to MYMIV infection. Correlation of reflectance at 688 nm (R688) and spectral reflectance ratio at 750nm and 445 nm (R750/R445) with the weighted mosaic index indicated that detection of yellow mosaic is possible based on these sensitive bands. Das et al (2013) conducted field experiment on yellow mosaic virus infected soybean leaves. Normalized Difference Vegetation Index (NDVI), Ratio Vegetation Index (RVI), Greeness Index (GI), Photochemical Reflectance Index (PRI) and Leaf Moisture Vegetation Index 1 (LMVI1) were computed and it was observed that NDVI was found to be useful in detecting yellow mosaic virus infected soybean.

Safflower:

Studies demonstrated the utility of ground based hyperspectral remote sensing for assessing certain biotic and abiotic traits associated with safflower (Prabhakar et al., 2012b). Normalised Pigment to Chlorophyll Index (NPCI) had highest correlation (r=0.78) with the measured chlorophyll. Regressing the NPCI upon measured chlorophyll resulted in a linear functional relationship, when validated with independent data set showed promising results. NDVI and LAI measured during flower initiation stage showed strong relation with dry matter, biomass and seed yield. Mean reflectance spectra between healthy and *Allernaria* diseased plants showed a distinct separation of bands in visible, NIR and SWiR regions. Among several hyperspectral Indices tested, Red edge Normalised Difference Vegetation Index, Normalised Pigment Chlorophyll Index and Normalised Difference Vegetation Index were found superior for detection of *Allernaria* disease at early stages of infestation.

Conclusions:

Remote sensing technology is reliable and provide accurate information to guide decision-making in crop pest management. The narrow bands in the hyperspectral remote sensing are able to measure the characteristic absorption peaks of plant pigments more precisely and thereby provide better information related to plant health. But availability of hyperspectral data from satellite platforms is only to a limited extent. In this context, the future of use of remote sensing in agriculture in general and in pest management in particular depend on making Unmanned aerial vehicles (UAV), popularly known as drones. There is need for more research efforts to identify pest/ disease specific sensitive bands at narrow wave bands (hyperspectral), spectral vegetation indices (SVI), image acquisition, analysis and interpretation of data from UAV platforms. Effective use of IOT, artificial intelligence (AI) and big data analytics, integrated with remote sensing technologies would become a rapid and effective tool that provide information on spatial variability of pest infestations in real time.

This would eventually help in guided field scouting for identifying pest infestation from large areas, that would save time, resources and enable for area-wide past management in future.

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Role of IPM in Sustainable Crop Productivity

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Introduction

To feed the increasing population, crop productivity had to be enhanced and there came the role of modern molecules of pesticides. While to develop one molecule of pesticide, it takes several years and huge investments, due to their misuse and abuse, i) within no time the pests are developing resistance to the molecule, ii) causing soil, water and air pollution and iii) the costs have become prohibitive. Hence, the concept of Integrated Pest Management (IPM) was introduced in 1967 where based on the knowledge of pest biology and ecology in conjunction with prevailing climate. IPM is a tactical combination of common-sense practices advocated to optimally manage the pests (pathogens, weeds, insects, vertebrates) in an ecologically and economically sound manner while safe-guarding the beneficial non-target species. In 1985 India declared IPM as official Ministerial Policy. Over the years IPM underwent several changes in its focus and approaches. Inspection; scouting and monitoring; pest identification; record-keeping and evaluation are fundamental to IPM. Monitoring and managing pest levels would not only reduce input costs but also preserve the environment, and protect the health of humans and animals including birds, bees, butterflies, predaceous bugs, and other pollinators. A sustainable IPM strategy requires profound knowledge of pest biology; all available methods of management; and judicious and targeted use of pesticides to reduce pest pressure as a long-term pest prevention or suppression with limited recourse to repeated intervention.

Components of IPM

Various methods are adopted for managing the crop-pests. They could be grouped into categories such as i) host resistance; ii) cultural practices; iii) biological methods; iv) chemicals; v) mechanical methods; vi) physical methods; vii) regulatory approaches and viii) genetic methods.

a. Host resistance

Host resistance is one of the cheapest and safe methods of pest management. The land races are endowed with genes for resistance and they are used in breeding programs to generate pest/pathogen resistant varieties. Against many insect-pests, only tolerant varieties could be developed (esp. when the resistance is polygenic), with lesser yields. For instance, desi cotton varieties are tolerant of white fly and the bollworm than American cotton varieties. On the contrary, where the resistance is controlled by mono- or oligo- genes, esp. against plant pathogens such as wheat rusts, the success has been tremendous. Biotechnological tools have been used to develop resistant varieties and most successful examples have been Bt cotton and ring spot resistant papaya varieties. However, care must be taken to ensure that such cultivars do not pose new threats as in case of the potato cultivar Lenape or wheat cultivar Paha. To minimize race development and resistance failure, gene deployment on a regional basis to avoid a genetic monoculture, or planting mixtures of cultivars to ensure some component of the crop will be resistant have been recommended.

b. Cultural practices

Based on the principle that certain pests display host-specificity, crop rotation is recommended to reduce/check pest populations. The infestation of stem borer of rice may be checked by cultivating jute after rice. Similarly, Jute hairy caterpillar can be controlled by cultivating rice after jute. *Aschochyta* blight of lentil can be reduced by crop rotation and use of healthy seed. Take-all of wheat (*Gaeumannomyces graminis*) and soybean cyst nematode (*Heterodera glycines*) could be managed by short rotations of one and two years, respectively. Some pests are normally carried from the old portion to new one, usually in fruit trees. Destruction of crop residues could help to reduce pests like stem borer of rice and sugarcane, cucurbit beetles etc. Destruction of crop residues infected with soil-borne plant pathogens such as *Macrophomina* or *Fusarium* will help to reduce inoculum and thereby break the disease cycle. Burning can effectively eradicate Dutch elm disease or citrus canker or halo blight of bean. However, burning agricultural fields has turned out to be a serious environmental concern. Pruning of the infested portion of apple with aphids or peach leaf curl or aphid of stone fruits and destroying the same will keep the pest under check. Similarly, thinning can help to reduce green leaf hopper damage in rice. Through balanced nutrition also, the overall health of the crop can be managed and thereby reducing pest incidence. Excessive nitrogen fertilization has been shown to increase susceptibility of rice to bacterial leaf blight, sheath blight, blast and leaf folder or whitefly in cotton. Clean culture is another approach that eliminates infected portions of crop, removes alternative hosts. Rhinoceros beetle live in cow dung, whereas Epilachna and red pumpkin beetles remain in dried leaves. Verticillium wilt, Fusarium wilt, black root rot, tobacco streak virus and Alternaria leaf spot pathogens can also infect common weeds found in cotton growing areas. Hence, destroying them will help to restrict spread of these diseases. Sub-terrestrial insects such as cutworm, termite, sugarcane white grubs *etc*. are controlled by flood irrigation. On the contrary, rice Caseworm infestion can be management by draining out water from the field. Okra is planted around or center of the cotton field as a trap crop to control the jassids and spotted Bollworms. Crotalaria plants trap the juveniles of the root-knot nematode *Meloidogyne* sp. and *Solanum* *nigrum* reduces the populations of the golden nematode *Heterodera rostochiensis*. Use of healthy seed prevents many pests and pathogens. This reduces stand loss. Use of healthy chickpea seeds reduced Aschochyta blight. Similarly, infestations of pink bollworm of cotton and citrus scale can be minimized by using healthy certified seed. Variation in time of plant and harvesting could be another mechanism. For instance, early sown sorghum escapes shoot fly attack. Other examples of crops that benefit from early planting include corn (corn ear worm, rust), beans (rusts, viruses, heat damage) and squash (stem borer, pickle worm, downy and powdery mildew, viruses). Late summer/early fall plantings of these crops may also be beneficial for avoiding pests. Earthing-up also helps to manage sugarcane early shoot borer and potato tuber moth as it prevents insects to lay their eggs.

c. Biological methods

Biological methods, otherwise known as biocontrol methods include use of other living organisms for the management of pests and pathogens. Predators are the organisms with body size greater or equal to the pest insect. Some common predatory arthropods include lady bird beetle (on aphids), *Chrysoperia carnea* (on all soft bodied insects), and *Cryptolaemus montrouzieri* (on mealy bugs) etc. On the other hand, parasitoid larvae feed internally or externally on the body of other insects. Adult parasitoids lay their eggs in, on or near their host insect. When the eggs hatch, the immature parasitoids feed on insects. *Encarsia formosa* (on whitefly) and *Gonatocerus ashmeadi* (on glassy winged sharp shooter). *Helicoverpa armigera* is parasitized at egg stage by *Trichogramma chilonis*, at larval stage by *Bracon hibitor* and by *Goniopthalmus halli* at pupal stage. *Epiricania melanoleuca* parasitizes adults of sugarcane pyrilla.

In addition to predators and parasites, several microorganisms also colonize insect pests. The commercial examples include *Bacillus thuringiensis* (on lepidopteran larvae); *Paenibacillus popilliae* (on Japanese beetle); *Beauveria*, *Metarhizium* and *Paecilomyces* spp on lepidopteran pests; *Lecanicillium* spp. on sucking pests; *Metarhizium* spp. against beetles, locusts and other grasshoppers, Hemiptera and spider mites; *Purpureocillium lilacinus* against rootknot nematodes; and *Trichoderma* spp., *Pseudomonas* spp., and *Bacillus* spp against major soil-borne plant pathogens. While Nuclear polyhedrosis viruses (NPV) and granulosis viruses (GV) are used against lepidopteran pests, *Steinernema glaseri* is an EPN recommended against white grubs.

d. Chemical control

The increased onslaught of biotic stresses due to intensive crop production systems necessitated use of synthetic pesticides since late 60s. However, over last few decades, excessive usage of these molecules leading to environmental hazards has led to development of safe pesticides coupled with their reduced usage. Some of the common insecticide groups include organophosphates, organosulphurs, carbamates, dinitrophenols, organochlorines, organotins, pyrethroids, spinosins, pyrazoles, pyridazinones, quinazolines, botanicals, synergists, antibiotics, fumigants, inorganics, and biorationals. Some of the common fungicides include inorganics, halogenated substituted monocyclic aromatics, chloroalkylthiodicarbamates, anilinopyridines, carbamic acid derivatives, conazoles, morpholines, amides and others. Most of the bactericides include antibiotics. While some molecules are systemic in nature giving prolonged protection, others are non-systemic and and act as contact pesticides. Of late, a combination of both systemic and contact pesticide formulations are also being marketed for effective pest management. However, their use is being questioned in recent times due to their impacts on human and animal health.

e. Mechanical control

The mechanical methods are mostly focused on eliminating the pest/pathogen. These include, hand-picking (egg mass of rice stem borer, early stage larvae of jute hairy caterpillars, adult of sugarcane stem borer); use of bag net (rice hispa, to some extent) or hand net (green leaf hopper, grasshoppers); hooking (rhinoceros beetle, jackfruit beetle); shaking plants or small trees or shrubs (cotton bug, mango shoot borer); sieving and winnowing (red flour beetle and rice weevil); burning (locusts); crushing and grinding (sugarcane shoot borer); sound production (wild boars, birds); rope dragging in field (rice case worm larvae); banding the trees (mealy bugs on mango); bagging the fruits (citrus fruit sucking moth, pomegranate oily spot); trenching the field (army worm, grasshoppers); tin collars on stem (rats); mechanical traps; light traps(leaf hopper, Jute hairy caterpillar, moths, stem borer of rice); air suction trap (stored grain pests); pheromones traps; and installation of bamboo cage cum bird perchers. Intercropping and mixed cropping systems work has physical barriers for the movement of wind-borne pathogen propagules within the field. Crop mosaics (different crops as well as different varieties of same crop) also function as physical barriers.

f. Physical control

Prior to the discovery of plant protection chemicals, physical methods were in vogue for management of crop pests. Application of heat such as super heating of empty godown to a temperature >50^{0}C for 10 -12 hours to destroy stored grain pest and sun-drying of the infested grains to kill adult insects; refrigeration at 5^{0}C or sub-zero temperatures of all eatables including dry fruits and stored grains; manipulating the moisture content in grains to minimize storage pests; extended soaking of logs to destroy boring weevils; ionizing radiation to make pest-sterile conditions; and use of ultrasonic sound as repellant are some of the examples. Soil solarization has been proved to reduce incidence of soil-borne pathogens and at the same increase the population of beneficial microorganisms and thereby improving plant health.

g. Regulatory approaches

Regulatory approaches refer to prevent the entry or spread of pests into an area or a country via inspection, quarantine, destruction of infested material, and other methods. Quarantine is a legal restriction method to prevent the spread of pests from infested to uninfected areas by restricting movement of infested plant materials. When such systems fail, accidental introductions of new pests are encountered. Some of the examples of introductions to India are *Icerya purchase* from Australia, *Eriosoma lanigerum* from Europe, *Quadraspidiotus perniciosus* from China, *Pthorimaea operculella* from Italy and *Liriomyza trifolii* from California, banana bunchy top virus and Phytophthora root rot (*Phytophthora cinnamomi*) *etc*.

h. Genetic control

These are modern methods of pest management wherein genetically manipulated sterile males as in cattle screw worm fly, *Cochliomyia hominivorax* in Curacao Island were released in to the wild population to reduce matings. Similar approach was adopted for the management of mediterranean fruit flies (*Ceratitis capitata*), boll weevils (*Anthonomus grandis*), horn flies (*Haematobia irritans*), tsetse flies (*Glossina* spp.), pink bollworms (*Pectinophora gossypiella*), and codling moths (*Cydia pomonella*). Similarly, lethal genes are introduced into the eggs of the females so that they do not develop beyond a certain stage.

Basic principles of Integrated Pest Management

The basic principles of IPM include agro-ecology approach, pest surveillance, economic threshold levels, and formulation of modules using available pest management options. The module formulation should consider the monetary cost of the option as well as ecological cost. Also, timing of the option in the module is critical to maximize the returns from the IPM strategy.

a. Agro-ecology approach

Management of pests/pathogen is a function of the crop production system, natural biophysical resource base (weather, climate, soil and water), predominant pest-pathogen complex, natural enemies and other biological species. The population dynamics of the pest/pathogen is an outcome of this interaction. The most effective system for managing the pests can be derived only after understanding the principles responsible for the population fluctuation in the given ecosystem.

b. Pest Surveillance

Pest Surveillance is another important pillar that helps in regular monitoring of the crop phenophase, pest/pathogen appearance and its development and corresponding bio-physical factors. This information will help to determine the level of incidence, estimated loss under when coupled with current and predicted weather conditions and economics of the management option. It will also help to identify the threats that need application of exclusion/eradication principles.

c. Economic Threshold Levels (ETL)

It is the level at which a given pest need to be considered for applying management measures. As long as the pest population are below ETL, the crop does not suffer economic losses. Coupled with current as well as future weather conditions, the projected ETLs will be ideal tools for appropriate pest management option.

d. Application of minimum selective hazards

All pest management options should focus on minimum damage to the non-target pest populations that are otherwise beneficial, reduced environmental hazards and avoiding/delaying the development of pesticide-resistant pest populations. When pesticide is deemed necessary, care should be taken to ensure i. efficacy against most vulnerable life stage of the pest, ii. least disturbance in the ecosystem and iii. Applied to ensure its distribution within the target area only to avoid unforeseen pollution/damage to beneficial organisms.

Thus, a successful IPM module is location/area and production-system specific, knowledge intensive and dynamic to consider all possible combinations as per the situation. For IPM to be successful, a basket of options should be made available to the stakeholders and specific configuration as suggested by the experts should be employed for effective management of the pest/pathogen.

Some Successful Models

Several success stories about IPM have been documented by National Centre for Integrated Pest Management and also Department of Plant Protection & Quarantine which are available on the respective websites. But most of them are crop/pest specific. For instance, to manage cotton mealy bug, IPM package comprising need-based application of chlorpyriphos in fields infested with weeds; removal of Parthenium and dumping in trenches; spray with *Verticillium lecanii*/chlorpyriphos (June to September); application of malathion dust around heaps of dry cotton sticks; disposal of cotton Sticks; regular monitoring for mealybug appearance and spot application of profenophos Only on infested plants to conserve the natural ecosystem; physical carrying of pest; and organizing periodic meetings with farmers to protect natural parasitoids was demonstrated by NCIPM. *Trichoderma* sp. are extensively recommended for the management of soil-borne plant pathogens in conjunction with seed-treatment fungicides as well as some of the pesticides. An integrated disease management package for management of foliar diseases of groundnut comprised i) seed treatment with carbendazim, ii) intercropping of groundnut with pigeonpea (3:1) ratio and iii) one spray each of 2% neem leaf extract, mixture of carbendazim and mancozeb (0.05%+0.2%) and iii) cell-free culture filtrate of *Penicillium islandicum* at 40, 55 and 70 days after sowing (Ghewande et al., 1993). Similarly, i) summer ploughing of the field, ii) seed treatment with carbendazim @ 2 g/kg of seed; iii) furrow application of *Trichoderma harzianum* @ 50 g culture mixed in 50-kg farmyard manure before sowing; one spray each of Nimbucidin (250 ml in 50 lit water) and carbendazim (50 g)+mancozeb (250 g) in 50 lit of water; harvesting plants at 75 % pod maturity level; placing harvested plants upside down for 3 days to avoid contact between the pods and wet soil,; removing insect-damaged and diseased pods and storing fully dried pods in polythene-lined gunny bags with fused calcium chloride reduced aflatoxin contamination in groundnuts below tolerance limits.

Current gaps in IPM

By concept, IPM is highly knowledge intensive and advocates optimized use of local resources. Though, a very good eco-friendly approach, IPM could not take off due to lack of a participatory research approach by making farmers an integral part. Another major disadvantage is optimized integration of components encompassing all biotic stresses and its large-scale demonstration. Most of the recent IPM schedules also list and describe management options to the specific context rather than their combined use to harness the synergy. Majority of the modules are based on a single pest, a single crop, a specific context, without a broader approach taking into account all biotic stresses as a socio-technical non-generic wholesome recommendation. The dynamic nature of the IPM modules corresponding to the new research findings and changing pest scenarios has seldom been addressed and hence, could not draw the attention of the farmers. The Department of Plant Protection and Quarantine (DPPQ) has published a series of bulletins on IPM and their successful application for many crop commodities. The Central Integrated Pest Management Centres working under DPPQs are

Fig 1. CIPMC Network in India

distributed across the country (Fig 1). However, their role as stand-alone systems cannot achieve the expected outcomes to expand the network of the IPM practitioners.

Way forward of IPM

IPM is a very good and eco-friendly concept to promote need-based use of hazardous pesticides, and optimized use of local low-cost or non-cost inputs resources to reduce cost of cultivation in managing biotic stresses and at the same time enhancing overall farm profitability. To realize this novel outcome, instead of crop-based IPM modules, production-system based IPM modules should be developed, tested and demonstrated. Involvement of the farmers should be encouraged while formulating research programs on pest management, spread the empirical knowledge on beneficial organisms, document and evaluate traditional knowledge on plant protection. Properly laid out surveillance programs should be taken up regularly to ensure that unforeseen pest onslaughts could be warranted. The synergy or antagonism among various components of pest management should be fully understood before recommending them for adoption. A well-oiled harmony among crop protection scientists and social scientists is essential to promote IPM strategies to fill the gap between researchers and farmers. Farmers should be trained about beneficial organisms and importance of ecosystem services for enhanced adoption of IPM modules. An overall understanding about farmers' education level, socio-economic conditions, environmental concerns, ethical values, regulatory frameworks, public policies, bouquets of management options, extension & training, consumer preferences and market characteristics will help to guarantee success of IPM concept. The CIPMCs of the DPPQ, research institutes, line departments and farmers should work in close collaboration, if the IPM strategies should succeed as viable pest management option.

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Impact of Climate Change on Insect Pests and Prediction of Pest Scenarios

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Introduction

Impacts of climate change are decipherable and evident. Global Mean Surface Temperature (GMST) and atmospheric CO_2 concentrations have been increasing at an alarming rate since last 19th century. The projected increase in temperature by 2100 was set at 1.4 – 5.8°C with the increase in the amount of CO_2 in the atmosphere by about 40% when compared with pre-industrial levels. The increase in the amount of CO_2 in the atmosphere would reach 500 to 1000 ppm by the end of 21st century (IPCC, 2014). Climate change is global phenomenon in its occurrence and consequences and more adverse effects are being experienced by the developing countries like India. Elevated carbon dioxide (eCO_2) and increase in temperature (*e*Temp) have implications in agriculture sector influencing crops and herbivore insect pests.
Global atmospheric carbon dioxide (CO_2) levels continue to increase rapidly, mainly because of the burning of fossil fuels. The atmospheric concentration of CO_2 has increased from a preindustrial level (1750) of 270 ppm to a current level of 394 ppm, an increase of 124 ppm, or 45% (Global Carbon Budget.org). Most studies indicate that CO_2 levels will at least double from preindustrial levels over the next five to ten decades. This increase represents one of the most large-scale and wide-reaching perturbations to the environment (IPCC, 2014). Over the past 20 years of research carried out by many of authors across the globe generated general understanding of the direct effects of increasing CO_2 concentration on plant growth and function. The most commonly observed effects of elevated CO_2 on insects are indirect (Murray et al., 2013). These indirect effects occur because of changes in plant physiology and biochemistry.

Elevated CO_2 levels generally lead to the accumulation of carbohydrates in the leaf tissue of plants through increased photosynthetic rates, causing an increase in leaf carbon (C) to nitrogen (N) ratio (Robinson et al., 2012). Since N is considered a limiting nutrient for insects this dilution of N reduces the nutritional quality of the leaves. In addition to decreases in leaf N concentration, changes in plant chemical defenses have been documented under elevated CO_2 and these changes could further impact herbivore performance (Robinson et al., 2012). Since climate is the direct input into the agriculture production process, the agricultural sector has been a natural focus for research. These changes affect the growth and development of the crop plants. Environmental change is anticipated to negatively, affecting both plant and insect populations.

Herbivores are primary consumers and get energy from plants or plant products. The impact of climate change on herbivorous insects can have far-reaching consequences for ecosystem processes and may alter significantly (Cornelissen, 2011). In many cases, the changes caused by enriched CO_2 bring about a reduction in its quality as a food source to herbivores, which affects herbivore performance. As herbivores are affected, so are higher trophic levels organisms (secondary consumers) are also get affected. While the effects of elevated CO_2 on interactions between individual herbivore species and their host plants are becoming better understood, little is known about how these effects may flow on to secondary consumers (predators and parasitoids) and thus affect whole food webs. Atmospheric CO_2 levels may affect the performance of natural enemies and/or susceptibility of prey directly or indirectly.

Elevated CO_2 levels and insects

The impacts of CO_2 on insects are indirect i.e., impact on insect damage results from changes in the host crop. Some researchers found that rising CO_2 can potentially have important effects on insect pest problems. Recently, free air gas concentration enrichment (FACE) and Open top chamber (OTC) technologies were used to create an atmosphere with CO_2 concentrations like what climate change models predict for the middle of the 21st century.

The atmospheric CO_2 concentrations have increased by above 20% and elevated CO_2 effects the plant growth and range of physical and chemical characteristics of the plant/crop. These include reduction in the leaf nitrogen content, changes in the defense compounds, water content, carbohydrates and leaf thickness. Indications are that exposure to elevated CO_2 levels will increase the plant photosynthesis, growth, above ground biomass, leaf area, yield, carbon and C: N ratio. These changes can influence the food quality for herbivorous insects and was well reviewed (Hunter, 2001). These changes in the leaf quality are likely to have varied effect on the performance of insect herbivores. The information on effect of elevated CO_2 on insect pests was compiled and presented by Srinivasa Rao *et al.* (2008a).

Chemical composition of some plant species changes due to biotic and abiotic stresses. As a result, their tissues became less suitable for growth and survival of insect pests (Sharma, 2002). Insect-host plant interactions will change in response to the effects of CO_2 on nutritional quality and secondary metabolites of the host plants. Increased levels of CO_2 will enhance plant growth, but may also increase the damage caused by some phytophagous insects (Gregory *et al*., 2009). Coviella and Trumble (1999) observed that in the enriched CO_2 condition, the insect confront less nutritious host plants that may extend their larval developmental times. Increased CO_2 may also cause a slight decrease in nitrogen-based defenses (e.g., alkaloids) and a slight increase in carbon-based defenses (e.g. tannins). Compensatory feeding is one way by which consumers may be able to mitigate some of the negative effects of reduced plant quality under elevated CO_2 conditions. Compensatory feeding is often exhibited by herbivores, especially mobile leaf chewers, in response to the reduction in host plant quality under elevated CO_2 levels. Yet, such compensatory feeding is often incomplete, because many species continue to exhibit a significant reduction in growth rate (Lindroth, 1996).

Succinctly the information on CO_2 impacts indicated that the performance of the same insect varied from host to host-indicating host species specificity. The analyzed data on impact of elevated CO_2 on insect pests reported a general decrease in foliar nitrogen concentrations and increase in carbohydrate and phenolic (secondary) metabolites. The consumption by herbivores was related primarily to changes in nitrogen and carbohydrate levels.

Increased temperature and insects

Climate change resulting in increased temperature could impact insect pest populations on agricultural crops in several complex ways. Although some climate change effects might tend to depress insect populations, most researchers seem to agree that warmer temperatures in temperate climates will result in more types and higher populations of insects. Increased temperatures can potentially affect insect survival, development, geographic range, and population size (Bale *et al.*, 2002). Temperature can impact insect physiology and development directly or indirectly through the physiology or existence of hosts.

Insects rely on an external heat source to regulate their body temperature and metabolism and thus changes in temperature have a direct impact on insect development rate and hence on population growth. In a scenario of climate change with a predicted rise of up to 4.8°C in global average temperatures by the end of this century along with an increasingly frequent occurrence of climate anomalies (IPCC, 2014), insect population dynamics can be drastically varied. Evidences suggest an acceleration in insect development rate under climate change, causing an increase in voltinism. This faster development raises insect food consumption rate and can accelerate the evolution of resistance to pesticides and to climate change. However, negative impacts of climate change on insects, such as local extinctions and asynchrony between insects and their hosts are also expected. Because the response of insects to temperature is species-specific and the intensity of climate change is locally dependent, studies on the effects of climate change should be evaluated for each species and location.

Increased temperatures will accelerate the development of several types of insects (cabbage maggot, onion maggot, European corn borer, Colorado potato beetle) and can lead to possibility of occurrence of more number of generations (and crop damage) per year (Bale *et al.*, 2002; Srinivasa Rao *et al.*, 2009). Recent studies on prediction pest scenarios under climate change scenarios conducted by authors indicated that the *S.litura* on groundnut (Srinivasa Rao et al 2015) and *H.armigera* on pigeonpea (SrinivasaRao et al 2016) were expected to have two to three additional generations during distant and very distant future climate change periods due to increased temperature across majority of locations of India.

Climate change influences the dynamics of individual species and communities. The effect of increasing temperature on number of generations of insect is well known and more evident in temperate climate and also to some extent in tropical climate. The increase in surface temperature would cause insect species to produce more number of generations with deduction of generation time. The phenology based models for various insect pests indicated that the possibility of occurrence of additional generations with increased temperature in future climate change (Kiritani, 2006).

Insects that spend important parts of their life histories in the soil may be gradually affected by temperature changes as compared to those that are above ground simply because soil provides an insulating medium that will tend to buffer temperature changes more than the air (Bale *et al.*, 2002). It is to conclude that the diversity of insect species and the intensity of their feeding have increased historically with increasing temperature.

Findings of CRIDA

Several experiments were conducted using open top chamber (OTC) facility to study the impact of elevated CO_2 levels on insects. Three square type open top chambers (OTC) of 4x4x4 m dimensions, were constructed at CRIDA, Hyderabad, two for maintaining elevated CO_2 concentrations of 700±25 ppm CO_2 and 550±25 ppm CO_2 and one for ambient CO_2. An automatic CO_2 enrichment technology was developed by adapting software SCADA to accurately maintain the desired levels of CO_2 inside the OTCs. The concentration of CO_2 in the chambers was monitored by a non-dispersive infrared (NDIR) gas analyzer. Castor, groundnut plants were grown in the three OTCs and also in the open, outside the OTCs. CTGC is a Carbon dioxide and Temperature Gradient Chamber, designed facility for measuring the impacts of elevated CO_2 and temperature which are vital parameters of climate change. The chamber is with field like environment with higher CO_2 and warming conditions concurrently which influence the crop growth and insect pests. This facility is first of its kind to simulate the future climate change scenario conditions with both CO_2 enrichment and warming conditions. (Srinivasa Rao et al 2018b)

- Larval duration or time from hatching to pupation in larvae of both the species (*Achaea janata* and *Spodoptera litura*) was significantly influenced by the CO_2 condition under which castor leaves offered to them. Larval duration of both species was extended by about two days when fed with elevated CO_2 foliage (Srinivasa Rao *et al*., 2009). Larvae ingested significantly higher quantity of elevated CO_2 foliage compared to ambient CO_2 foliage. For instance, *A. janata* consumed 62.6% more of 700 CO_2 foliage than 350 CO_2 chamber foliage. The rate of consumption (RCR) was also higher in case of elevated CO_2 foliage. Thus, larvae fed with elevated CO_2 foliage consumed more each day and over a longer period, resulting in considerably increased ingestion.
- The efficiency of conversion of digested food into body mass (ECD) was lower with elevated CO_2 castor foliage for both species of larvae. The digestibility (AD) of elevated CO_2 foliage was significantly higher than ambient CO_2 foliage for both the species, more so in case of *S. litura* (Srinivasa Rao *et al*, 2009).
- Significant influence of elevated CO_2 on life history parameters of S.litura on groundnut was noticed and percent of variation of these parameters was significant under elevated CO_2 compared with ambient CO_2. The percent reduction of nitrogen content and increased percent of carbon, C: N ratio and TAE (Tannic acid equivalents) was significant in groundnut and castor foliage under elevated CO_2.

Impact of Climate change on Natural enemies

Climate change can have diverse effects on natural enemies of pest species. The fitness of natural enemies can be altered in response to changes in herbivore quality and size induced by temperature and CO_2 effects on plants. The susceptibility of herbivores to predation and parasitism could be decreased through the production of additional plant foliage or altered timing of herbivore life cycles in response to plant phenological changes. Impacts of increased CO_2 on plant-herbivore interaction may further influence the biological parameters of natural enemies at the third trophic level (Stiling et al., 2002) influencing the growth, development and reproduction, and predation/parasitization preference of natural enemies for herbivorous insects.

The three factors of climate change influence the occurrence of natural enemies of insects. Natural enemies are density dependent factors which depend on host population i.e., insect population (independent factors). The impact of climate change factors on natural enemies is more complex and critical. Differential responses by natural enemies to climate change were reported by several authors. As with temperature, precipitation changes can impact insect pest predators, parasites, and diseases. Fungal pathogens of insects are favoured by high humidity and their incidence would be increased by climate changes that lengthen periods of high humidity and reduced by those that result in drier conditions. There will also be instances where warmer conditions will increase the effectiveness of many natural enemy species and/ or increase the vulnerability of their prey (Thomson *et al*., 2010). Higher temperatures will favour parasitoids rather than their hosts (Kiritani, 2006). For those insects and their parasitoids with lower developmental threshold (T_o), it seems that they could match very well and the relationship might not be affected dramatically under global warming. Species that do feed longer to compensate the decreased nitrogen may become more vulnerable to natural enemies as in case of gypsy moth (Hochuli, 1996). The natural enemy populations on the aspen trees inter-planted with the birch tress exhibited strong positive responses to elevated carbon dioxide (CO_2) and negative responses to elevated ozone (O_3) (Percy *et al*., 2002).

Quantification of the direct and indirect effects of temperature and elevated CO_2 (eCO2), on tritrophic interactions of cowpea (*Vigna unguiculata* subsp. *unguiculata* L.), legume aphid *Aphis craccivora* Koch and coccinellid predator *Menochilus sexmaculatus* Fab. Indicate that reduction of the leaf nitrogen (6%), aminoacid (6%) and protein (7%) of cowpea foliage with increased carbon (13%) and C:N ratio (21%) at eCO2 overaCO2 indicated the dilution of biochemical constituents at first trophic level. Shortened development time, DT and increment of reproductive rate, RR at eCO2 over ambient CO_2 (aCO_2) was significant with increase in temperature from 20 to 35 °C. The ‘rm’ and ‘Ro’ increased gradually with increase in temperature followed the non-linear trend and reached maximum values at 27 °C with shortened ‘T’ across 20 to 35 °C temperatures at eCO_2 indicating the significant variation of growth and development at the second trophic level. Decreased grub duration (23%) with increased predation capacity (19%) of *M. sexmaculatus* on *A. craccivora* at eCO_2 over ambient was noted, indicating the incidence of *A. craccivora* is likely to be higher with increased predation also in the future climate change scenario (Srinivasa Rao et al 2018a)

Prediction of Pest Scenarios during future climate change periods

The prediction of possible pest situation in the future period based on elevated CO_2 and increase in temperature will indicate the expected possible pest scenarios. The predicted pest scenarios will improve the preparedness of the farmer to tackle the pest situation effectively. Insects (and mites) are cold blooded organisms and therefore their development rate is directly related to temperature – as temperatures get warmer insects develop faster. In addition, most insects have a lower and upper temperature development threshold, below or above which, respectively, they do not develop. Prediction of pest scenarios using different approaches viz., thumb rules, simple pest models, accumulation of degree days and construction of life tables etc are being attempted.

Thumb rule: The successful and standard thumb rule developed for Helicoverpa by NCIPM was used to predict pest incidence during future climate change periods. Thumb rule indicates that "if rainfall during month of June-sept is below the normal (500±25 mm) and rainfall during the month of November is above the normal (10±3 mm) then pest incidence will be severe on pulses". The future climate data was down scaled for various areas of the country using PRECIS A1B Scenario data. Results indicated that the predicted pest incidence would be low during (2020) and moderate during 2050 and 2080 years at Gulbarga and Hyderabad regions. (Srinivasa Rao et al, 2008a).

Simple pest models: The future projected data were obtained from UK met office using Had CM3 model output under A2 a scenarios for 2020, 2050, 2071 to 2100 years. This data on precipitation, minimum temperature and maximum temperature were collected grid wise and used for prediction purpose. The data was converted to daily and standard week wise and utilized for estimating the pest scenarios using simple pest models which were developed at CRIDA. The predicted results indicated the incidences of Castor Semilooper and Helicoverpa would be severe during 2050,2086 and 2100. (Srinivasa Rao et al, 2008a).

Degree days: Growing degree days (GDD or DD) are a measure of the "heat units" (related to temperature and the amount of time per day that an insect spends actively growing) that accumulate over time. Studies were conducted to estimate the impact of increase in temperature on number of generations of tobacco caterpillar, *Spodoptera litura* on peanut for seven different locations of various agro ecological zones of the country for baseline (1961 to 1990) near future (2021 to 2050) and distant future (2071 to 2098) climate change (A1B) scenarios. Faster accumulation of degree days will be making it possible for one or two additional generations with shortened life cycle (completion of generation would be 5 to 6 days earlier) of *S. litura* was inferred for both near and distant-future climate change scenarios (CCS) compared to baseline and present periods, at all locations.

Life table approach: Investigations were conducted to understand the direct effects of rising temperature and the host mediated effects of elevated CO_2 (eCO_2) on *S.litura*. The thermal requirement of *S. litura* from egg to egg (within the range of 20 ^{0}C to 35^{0}C) was 538.5 DD on eCO_2 as against 494.5 DD on aCO_2 foliage. Finite (λ) and intrinsic rates of increase (rm), net reproductive rate (Ro), mean generation time (T) and doubling time (DT) of *S. litura* varied significantly with temperature and CO_2 and were found to have quadratic relationships with temperature. Prediction of pest scenarios based on PRECIS A1B emission scenario data at eleven peanut growing locations of the country during near future (NF) and distant future (DF) climate change periods showed an increase of 'rm' and ' λ' with varied 'Ro' and reduced 'T'. (Srinivasa Rao et al, 2014)

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Invasive and alien pest species- A threat to Indian agriculture: Role of ICAR-NBPGR in preventing their entry

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India is one of the important mega-biodiversity rich countries with 7-8% of the recorded species of the world. The three major parts of India, *viz*., Himalaya, Indo-Burma, Western Ghats have been identified as part of the 34 globally identified biodiversity hotspots. India is also recognized as one of the eight Vavilovian centers of origin and diversity of crop plants, having more than 300 wild relatives of crop species. Invasive alien species (IAS) are one of the major threats to this treasure of enormous agricultural biodiversity, forestry, livelihoods, human and animal health in the present regime of climate change. They may become responsible for the extinction of native species, change in habitats, cropping pattern in the area and affect agro-ecosystem and food security, human health thereby causing economic loss (Paini et al., 2016).

Invasive species is a species that has established and spread or has the potential to do so outside of its natural distribution range, and which then threatens ecosystems, habitats and/or other species, potentially causing economic and/or environmental damage, or harm to human health. An IAS is defined as an alien species, which becomes established in natural or semi-natural ecosystems or habitat, is an agent of change, and threatens native biological diversity (Sankaran et al., 2019).

Invasion by alien organisms occurs in four stages, i. Introduction, ii. Establishment, iii. Spread, and iv. Naturalization. Global warming, climate change, exponential increase in international trade of agricultural commodities in the Post-Convention of Biological Diversity (CBD) era, modernization in agriculture - changes in cropping patterns/agro-ecosystem, loss of forest cover etc are some of the major factors that led to the incursion of high incidence of exotic pests into India. India's rich biodiversity is highly susceptible to invasive species. Invasive alien species occur in all major taxonomic groups, however, the important ones for agricultural ecosystem include viruses, bacteria, fungi, nematodes, insect pests, algae, ferns, higher plants etc. Sandilyan et al., (2018) reported about 171 invasive alien species in different ecosystems of India, where invasiveness was confirmed based on the invasive attributes such as Invasiveness (invasive elsewhere; rapid multiplication and spread in different ecosystems; multiple modes of reproduction and multiple modes of dispersion); impacts (affecting ecosystem; biodiversity loss; economic loss and health hazard) and invasion areas (range extension). As per the report, in the Indian agricultural ecosystem, 21 insect species, 16 fungal, 5 bacterial, 3 viral and one nematode species were categorized as IAS based on the criteria mentioned above. In addition, 54 invasive alien terrestrial plant species and 8 aquatic invasive alien plant species were reported in India.

Bang et al (2021) estimated the average annual economic costs incurred by IAS to the Indian economy amounted to US$ 182.6 billion (i.e. total costs) and US$ 127.3 billion (i.e. when considering Observed and High reliability costs only) (Indian Rupees ₹ 11.9 trillion and 8.3 trillion, respectively) over the period 1960–2020. Earlier, Pimentel et al. (2001) reported that the Indian economy suffers US$ 116 billion per year as a result of IAS.

The historical Irish famine of 1845, caused by late blight of potato (*Phytophthora infestans*), introduced from Central America; coffee rust (*Hemelia vastatrix*) into SriLanka in 1875 and subsequent introduction to India in 1876 and powdery mildew (*Uncinula necator*), root eating aphid (*Phylloxera vitifolia*) and downy mildew (*Plasmopara viticola*) of grapes from central America to France in mid-19th century are some globally important examples of introduction and establishment of quarantine pests into new areas, affecting the crop productivity and thereby the country's economy.

India witnessed the first invasion of insect pest, San Jose scale, *Quadaraspidiotus perniciosus* [Hemiptera: Diaspididae] in 1879 from China and continued further leading to severe imbalance in crop and human ecosystems. Some of them were Serpentine leaf miner (*Liriomyza trifolii*), rugose spiralling whitefly (*Aleurodicus rugioperculatus*), tomato pin worm (*Tuta absoluta*), fall army worm (*Spodoptera frugiperda*) and Bondar's nesting whitefly (*Paraleyrodes bondari*), desert locusts (*Schistocerca gregaria*) attack during COVID Pandemic-2020 affecting the agro-ecosystem of the country, thereby causing huge economic losses over the years. Recently, *Thrips parvispinus* invaded the chilli ecosystem causing 40 to 80 per cent of the damage to chilli crop in Andhra Pradesh and Telangana which was presumed to be due to the change in weather and climatic conditions during the crop season (Sireesha, 2021). This invasive insect pest caused panic among the researchers and farmers in the country in the recent times.

In India, several other exotic pest incursions were reported and some of them are Fusarium wilt, caused by *Fusarium oxysporum* f sp *cubense*, Tropical race 4, which is renamed as part of the new species*, F. odoratissimum* affecting banana; wheat blast, caused by *Magnaporthe oryzae triticum* (*MoT*), white rust in chrysanthemum caused by *Puccinia horiana* in 2016, guava root-knot nematode (*Meloidogyne enterolobii*) etc. Wheat blast is a a newly emerged disease, first reported in Brazil in 1985 and spread to other wheat growing regions of Bolivia, Paraguay, and Argentina by 2007. The disease occurred in epidemic proportions in Bangladesh in year 2016, causing yield losses as high as 100% in some areas (Islam *et al.,* 2016). In view of this, the West Bengal government has banned wheat cultivation in the nine border districts in West Bengal within five kilometers of the

Bangladesh border and banned wheat production in Murshidabad and Nadia districts of West Bengal.

It is important to understand the pathways (Intentional introduction; trade; tourism; climate change effect etc) through which IAS are entering the country so as to develop management strategies. The natural invasion of desert locust (*Schistocera gregaria*) in South Asia and India was attributed to the changing climate (Meynard et al. 2020), while six species arrived as contaminants with seed and live material (i.e. *Aleurodicus rugioperculatus, Hypothenemus hampei, Paracoccus marginatus, Parthenium hysterophorus, Phalaris minor*, and *Spodoptera frugiperda*), whereas yellow fever mosquito (*Aedes aegypti*) arrived *via* stowaway. The two weed species (*Lantana camara, Mikania micrantha*) were intentionally released in India during the British rule. Few years ago, five new species of Invasive Alien weeds, *viz*., *Ambrosia trifida* (Giant Ragweed) *Cenchrus tribuloides* (Spiny Burr Grass), *Cynoglossum officinale* (Hound's Tongue), *Solanum carolinense* (Horsenettle), *Viola arvensis* (European field Pansy) have entered few states of India. The surveillance of these weeds in the states is being taken care of to minimize the losses due to further invasion (Saurabh Singh et al., 2016).

In India, the Directorate of Plant Protection, Quarantine and Storage (DPPQS), Faridabad under Ministry of Agriculture & Farmers’ Welfare, Government of India is responsible for implementation of the latest Plant Quarantine (Regulation of Import into India) Order, 2003 that was originated from the basic Destructive Insects and Pests Act, 1914 to prevent entry, establishment and spread of exotic plant pests into India along with the exotic crop germplasm. Quarantine processing of all the bulk imports (commercial) consignments is done at the plant quarantine and fumigation stations that have been established at various points of entry such as international airports, seaports, and land custom stations under the DPPQS following the guidelines given in the PQ Order, 2003. ICAR-National Bureau of Plant Genetic Resources is the nodal agency for the Plant Genetic Resources Management, and has been empowered for the issuance of Import Permit and to undertake quarantine processing of all imported plant genetic resources, including transgenics and trial material meant for research. ICAR-NBPGR Regional Station, Hyderabad deals with the quarantine processing of crop genetic resources meant for Southern India covering all State Agricultural Universities, ICAR Institutes, private Industry and International Organizations, viz., ICRISAT, CIMMYT, IRRI and AVRDC. National and international legislatory frame work in India, Quarantine regulations pertaining to the import of crop genetic resources, national plant quarantine set up in India, Quarantine procedures that are followed for import samples to prevent the entry of quarantine pests and regulated non-quarantine pests and future strategies to prevent the entry and invasion are discussed.

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Pest Survey and Surveillance for Pest Forecasting and Pest Management

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It is well known that in a cropping system, regular watching, scouting and keeping a vigil at regular intervals is vital to understand the pest dynamics. Pest survey is a detailed collection of insect population information at a particular time in a given area. The regular surveys of same place or locality at consistent intervals to assess changes in pest species over a time is called 'surveillance'. It is often defined as Pest surveillance is the watch kept on a pest for the purpose of decision making. depending on the kind of pests, surveillance programme attempt to determine if a pest species is present, to estimate the numbers in a population and their distribution and to assess how these factors change over time. Pest survey is a detailed collection of insect population information at a particular time in a given area. The regular surveys of same place or locality at consistent intervals to assess changes in pest species over a time is called 'surveillance'.

Pest surveillance: It refers to an official process which collects and records data on pest occurrence or absence by survey, monitoring or other procedures (ISPM No. 5).

It refers to the constant watch on population dynamics of pests, its incidence and damage on each crop at fixed intervals to forewarn the farmers to take up timely crop protection measures

Objectives of survey and surveillance: To monitor the pest population and /or damage regularly to arrive at a decision whether control measures are required or not, if required when to initiate the control measures. Pest forecasting with reasonable precision. Endemic areas of various pests may also be marked.

Objectives of Pest Surveillance

1. To know existing and new pest species
2. To assess pest population and damage at different growth stage of crop
3. To study the influence of weather parameters on pest
4. To study changing pest status (Minor to major)
5. To assess natural enemies and their influence on pests

6. Effect of new cropping pattern and varieties on pest

Three basic components of pest surveillance

- Identification of insect pest (collected, reared otherwise bar-coding IBOL: International Barcode of Life).
- Determination of pest population (useful in pinpointing factors that bring changes in natural population and understand functioning of life-system of pest species).
- The loss caused by the incidence (based on economic threshold level (ETLs) and the economic benefits, by the control measures.

Surveillance can provide necessary information to determine the feasibility of a pest control programme. Regular field surveillance (= monitoring) is an important component of integrated pest management (IPM). Surveillance helps prognosis i. e. foreseeing the population of pests, their interaction with natural enemies and the resultant effect. It is essential for the following activities associated with IPM. a. Ecological characterization of an area b. Acquaintance with pests, disease and beneficial insects c. Assessment of critical density d. Crop loss assessment.

Types of surveillance

1. General surveillance
2. Specific surveys

1. General Surveillance for

Use of information

- To support declarations of pest freedom
- To aid early detection of new pests
- To report to other organisations (FAO, RPPO, other NPPOs)
- To compile host and commodity pest lists and distribution records

Sources of information

- National Plant Protection Organization (NPPO) or designated institution acting as national repository for plant pest records

- Research institutions, universities, scientific bodies, Producers, consultants Museums, general public, Scientific and trade journals, Contemporary observations and Regional and international sources

Collection, Storage and Retrieval

- NPPO or other institution designated as national repository for plant pest records
- A record keeping and retrieval system
- Data verification procedures
- Communication channels to transfer information from the sources to the NPPO
- Incentives to report such as:
  - ✓ Legislative obligations
  - ✓ Cooperative agreements (between the NPPO & specific agencies)
  - ✓ Use of contact personnel to enhance communication to and from the NPPO
  - ✓ Public awareness/education programmes

Pest-specific surveillance approach should include the following:

- Identification of the target pest(s)
- Identification of scope (e.g. geographic area, production system, season)
- Identification of timing (dates, frequency, duration)
- In the case of commodity pest lists, the target commodity
- Indication of the statistical basis (e.g. level of confidence, number of samples, selection and number of sites, frequency of sampling, assumptions)
- Description of survey methodology and quality management based on an understanding of the biology of the pest, purpose of the survey and including an explanation of: —
- Sampling procedures (e.g. attractant trapping, whole plant sampling, visual inspection, sample collection and laboratory analysis)
- diagnostic procedures
- reporting procedures

The most successful surveillance programs carried out by the agencies are achieved through regular survey activities. An insect pest survey is a detailed collection of insect population information at a particular time in a given area.

Pest survey: An official procedure conducted over a defined period of time to determine the characteristics of a pest population or to determine which pest species occur in an area (ISPM No. 5). The survey programme may be carried on for an entire growing season or at certain critical periods in the insect life cycle. the area involved in a survey may be small as field, or it may be as extensive as state or region of the country. These surveys are usually carried out to determine the boundaries of an infestation or area infected rather than to define an area that is “free from a pest”.

Specific survey

- **Detection survey:** Survey conducted in an area to determine if pests are present. Detection surveys are appropriate if a pest’s presence in an area is not known.
- **Monitoring survey:** Ongoing survey to verify the characteristics of a pest population. Monitoring surveys are appropriate to document changes in prevalence of a particular pest population over time and to assist with pest management.
- **Delimiting survey:** Survey conducted to establish the boundaries of an area considered to be infested by or free from a pest.
- Delimiting surveys are usually used to define the boundaries of spread for a new, invasive pest. A delimiting survey often precedes the implementation of an eradication programme. Delimiting surveys may also be useful for shipping commodities outside of the pest range for a pest of limited distribution.

Specific survey should include: statistical basis, level of confidence, number of samples, number of sites, frequency of sampling and assumptions.

Should include a description of survey methodology and quality management system to explain:

Sampling procedures (attractant trapping, whole plant sampling, visual inspection, sample collection and laboratory analysis), Diagnostic procedures, Reporting procedures.

Types of survey

1. **Roving survey:**
    - Assessment of pest population/damage from randomly selected spots representing larger area, Large area surveyed in short period, Provides information on pest level over large area.
2. **Fixed plot survey:**
    - Assessment of pest population/damage from a fixed plot selected in a field.
    - The data on pest population/damage recorded periodic from sowing till harvest.

Ex: 1 sq.m. plots randomly selected from 5 spots in one acre of crop area in case of rice. From each plot 10 plant selected at random. Total tillers and tillers affected by stem borer in these 10 plants counted.

Total leaves and number affected by leaf folder observed. Damage expressed as per cent damaged tillers or leaves.

Population of BPH from all tillers in 10 plants observed and expressed as number/tiller.

3. **Qualitative survey:** it involves the identification of the different species of a region. qualitative survey may also limited to one or more of the following categories such as potential pests, actual pests and natural enemies, abundance etc.

- Qualitative survey: (detection of pest)
- Aimed at pest detection
- Provides list of pest species present along with reference to density like common, abundant, rare.
- Employed with newly introduced pests to understand the extent of infestation.
- Adopted at international borders (avoid invasion of any new species).

4. **Quantitative survey:** it involves measurement of the abundance of an insect. it is more efficient to estimate population density by sampling.

- Quantitative survey: (enumeration of pest)
- Define numerically the abundance of pest population in time and space.
- Provides information on damaging potential of a species and data can be used to predict future population trends.
- Provide the basis to decision making for adopting control measures.

Selection of survey sites

- Previously reported presence and distribution
- Biology of the pest
- Host plant distribution
- Climatic suitability of sites
- Probable points of entry
- Possible pathways of spread

Timing of survey procedures determined by:

- Life cycle of the pest
- Timing of pest management programmes
- Stage of growth/maturity of the host plant(s)/plant parts attacked

Sampling

A sampling technique is the method used to collect information for a single sample. A sampling program is the procedure for employing the sampling technique in time and space. Measurement taken to estimate population density (sampling methods) fall into 3 groups

I. Absolute methods
II. Relative methods
III. Population indices

I. **Absolute methods**: Absolute methods yield estimates as densities per unit area of land area in the habitat. Four distinct approaches have been used in Entomology to estimate absolute population densities. They are a. The distance to nearest neighbour approach b. Sampling a unit of habitat c. The recapture of marked individuals d. Removal trapping

II. **Relative methods**: Relative methods yield densities per some unit other than land area and cannot be converted to absolute estimates. The sweep net and black light trap are two of the most common methods used to sample insect population densities. Relative methods have distinct advantage over absolute methods, a given amount of labour and equipment yields much more data.

III. Population Indices: Population indices do not count insects at all but rather are measures of insect products such as plant damage, frass or nests. In some cases a species that is difficult to sample directly creates products that are easily sampled by absolute methods. The insect product most often sampled is the frass or excreta of Lepidopterous defoliators of forests. The rate at which frass is being produced can be estimated from the amount falling into box or funnel placed under the trees. The size and shape of the frass pellet are rather constant for given species and instar, this allows one to identify the species and age composition of the defoliators with out seeing the insect.

Pest monitoring:

Monitoring for pests is a fundamental first step in creating a proper integrated pest management (IPM) programme. Pests are monitored through a variety of monitoring tools such as pheromone traps, light traps, colored sticky traps, pitfall traps and suction traps.

- Monitoring is the process by which the numbers and life stages of pest organisms present in a location are established.
- The population size and the level of activity of beneficial organisms must also be determined for arthropod management.

The trap capture data serves several purposes:

I. Ecological studies
II. Tracking insect migration
III. Timing of pest arrivals into agro-ecosystems
IV. Initiating field scouting and sampling procedures
V. Timing of pesticide applications
VI. Starting date or biofix for phenology models and
VII. Reduction of later generations based on size of earlier generations

Monitoring Beneficial's is generally not as important for other pest categories. There is no single monitoring technique that works for all categories of pests, and even within a pest category the best technique differs due to pest biology and ecology.

For example: direct counting of nematodes in soil would require the use of different techniques than counting tobacco hornworm caterpillars on a tomato plant.

Pest surveillance and monitoring in India

Directorate of Plant Protection, Quarantine and Storage (DPPQS), Faridabad, is organizing regular rapid roving pest surveys on major field crops in different agro ecosystems in collaboration with ICAR and SAU’s and a consolidated report then issued by Plant Protection Adviser (PPA) to the Government of India.

Every year there is huge loss to the agricultural yield and productivity due to pest and diseases the reason being:

1. No proper and centralized database for analysis and forecasting of pest disease.
2. No on time advisory and early warning to the farmers to take appropriate action against the pest/ disease.
3. No authenticity of the survey data
4. Compartmentalized information, and many more.

Monitoring techniques

a) What to look for:

- ✓ Presence and evidence of pests
- ✓ Evidence of damage
- ✓ Nature of damage

- ✓ Where the damage is found
- ✓ Are there still pests present in the damaged area
- ✓ Presence of natural enemies
- ✓ Evidence of potentially contributing activities to the pest problem
- ✓ If unrecognized pests are found, samples should be collected and
- ✓ brought to the county extension office.

b) Frequency of monitoring

Determined by the biology of the pest

- ✓ Determined by the crop, if a crop has a low threshold of damage, more intensive monitoring may be needed at regular intervals (weekly and maybe more frequently when a pest approaches a borderline to becoming a threat to a crop)

c. Size of area to monitor

- ✓ Depends on the crop, the farm size, and the pest
- ✓ Enough to provide good field representation or coverage
- ✓ Depends on the degree of accuracy required and the resources available
- ✓ The field is surveyed in a pre-arranged pattern, such as walking in an S, U, Z, V or X shape

d. Record keeping:

- ✓ Accurate records are important for decision making and for evaluating trends in pest populations season to season
- ✓ If a monitoring form is developed, it should provide information on:
  - ▪ Both harmful and beneficial insects
  - ▪ Identification of the field and the sample date
  - ▪ Sample method
  - ▪ Units of sample, e.g. insects per tree, infected fruits per plant

Monitoring methods

a. Types of monitoring techniques

i. Visual counts over a representative area

- counting the number of pests present per plant, per leaf, per fruit, per terminal, per area bases
- damage counts which estimate pest population per plant, per area or per fruit (pre and post harvest)

ii. **Pheromone traps**
  - sticky traps which use pheromone bait to attract insects

iii. **Sweep nets**
  - need to use a standardized sweep
  - sampling locations need to be consistent
  - in some cases, sampling times need to be consistent

iv. **Field history, look for patterns of pest problems.**

b. **Monitoring for insect pests**

  – i. Visual counts
  – ii. Sweep nets
  – iii. Pheromone traps

Monitoring method for insect pests of cucurbits: Check fields twice per week by examining 50 plants per field when plants are small (up to 10 leaves) and as plants get larger, change the sampling plan to 100 leaves per field. The samples (either 50 plants (early season) or 100 leaves (mid to late season) should be taken so that all areas of the field are represented. The monitoring should start at a corner of the field, walking in an X or Z pattern

Pest Forecasting: This is the process of making predictions of the future based on past and present data and most commonly by analysis of trends. Forecasting of pest incidence or outbreak is based on information obtained from pest surveillance.

Uses

- Predicting pest outbreak which needs control measure
- Suitable stage at which control measure gives maximum protection

Two types of pest forecasting

1. **Short-term forecasting**: It covers a particular season or one or two successive seasons only and is usually sampled from a particular area within a crop using appropriate sampling technique and the relationship is established between weather data and progress in pest infestation.

   e.g. Wheat grain aphid, *Sitobion avenae* (Fab.) based on multiple regressions.

2. **Long-term forecasting**: These are based on possible effect of weather on the pest population and cover a large area or by extrapolating from the present population density into future.

   e.g. Management strategies for Brown Planthopper, *Nilaparvata lugens* (Stal) and White-backed Planthopper, *Sogatella furcifera* (Horvath).

Pre-requisites for developing a Forecast System

- The crop must be a cash crop (economic yield)
- The insect must have potential to cause damage (yield losses)
- The Insect pest should not be regular (uncertainty)
- Effective and economic control known (options to growers)
- Reliable means of communication with farmers
- Farmer should be adaptive and have purchase power

Criteria for successful Insect pest forecasting system

- **Reliability** -use of sound biological and environmental data
- **Simplicity** - The simpler the system, the more likely it will be applied and used by producers
- **Importance** -The insect pest is of economic importance to the crop,
- **Usefulness** -The forecasting model should be applied when the insect can be detected reliably
- **Multipurpose applicability** -monitoring and decision-making tools for several diseases and pests should be available
- **Cost effectiveness** -forecasting system should be cost affordable relative to available insect pest management tactics.
- Objectivity
- Consistency with scientific knowledge
- Adequacy to scales
- Timeliness
- Sensitivity to extreme events

Success of a forecasting

The success of a forecasting system depends, among other things, on

- The **c**ommonness of epidemics (or need to intervene)
- The accuracy of predictions of epidemic risk (based on weather, for example)

- The ability to deliver predictions in a timely fashion
- The ability to implement a control tactic (Insecticide application, for example)
- The economic impact of using a predictive system

Pest surveillance or monitoring is he corner stone of IPM (Grant et al., 2006) as compared to calendar-based treatments. IPM stresses monitoring of pest and determines when the action is necessary to be taken, the basic purpose of surveillance is to determine whether pests are present in the field at a level to initiate pest management interventions. Through regular and systemic pest surveillance epidemic situations can be avoided by detecting damage before endemic establishment of a pest in any area (Singh et al., 2012).

Uses of insect pest forecasts are many. Forewarning or assessment of insect pest important for crop production management and **For timely plant protection measures-**Information whether the insect pest status is expected to be below or above the threshold level is enough, models based on qualitative data can be used – qualitative models, **Loss assessment-**Forewarning actual intensity is required - quantitative model, **For making strategic decision-**Prediction of the risks involved in planting a certain crop. Deciding about the need to apply strategic control measures (soil treatment, planting a resistant cultivar etc) **For making tactical decision-**Deciding about the need to implement insect pest management measure: Entomologist and meteorologists have often collaborated to develop insect pest forecasting or warning systems that attempt to help growers make economic decisions for managing insect. These types of warning systems may consist of supporting a producer’s decision-making process for determining cost and benefits for applying pesticides, selecting seed or propagation materials, or whether to plant a crop in a particular area.

In case of studies relating to pest dynamics, it is essential to standardize methods of surveillance through carefully designed data recording formats relating to crops, pests, and production and protection practices in addition to weather. Implementation of pest surveillance across various different agroecological areas /zones gives clear cut understanding of climate and would help to draw the underlying mechanism of the observed pest status. Analyses with weather would further aid in delineating climate effects on pests. Making pest surveillance operational through provision of pest scouts and data entry operators make it possible to capture quality data at field level guided by scientific staff. Once quantified relationships are established after thorough pest surveillance, simple pest models can be developed for pest forewarning (Vennila *et al.,* 2016).

"Forecasting models in order to optimize timing of monitoring, management and control measures of insect pests"

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Use of Information and Communication Technology in Integrated Pest Management

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Introduction

Information and Communication Technology (ICT) commenced with the launch of World Wide Web in 1991. India had its first National e-governance plan in 2006 and the launch of 'Digital India' project in 2014. Digital India version 2.0 of 2021 aims to transform India into a digitally empowered society by facilitating wider dissemination of knowledge and technological products and processes for inclusive development of our nation in all spheres, and agriculture is not an exception. Transformation in agriculture is a continuous process and evolves with the needs of mankind and technological innovations of human minds on the sidelines of the vagaries of monsoon and climate change. While major components of crop production viz., high yielding cultivars, fertigation and irrigation directly maximize crop yields, crop protection targets to minimise yield losses due to biotic stress factors be it weeds, insects, pathogens, mites, nematodes, rodents, birds and vertebrates under pre- and post-harvest situations. Maximum yield loss to crops is estimated at 33% by weeds followed by insects (26%), diseases (20%), rodents (6%) and others (6-8%) with yield losses higher for fruits and vegetables (4.6-15.9%), followed by pulses (6.4-8.4%), cereals (4.7-6.0%) and oilseeds (3.1-10%) under Indian conditions. Paradigm shifts of pest management have gone through phases of Subsistence, Exploitation, Crisis, Disaster and Integration over decades.

Integrated pest management (IPM) has been a national policy since 1985 and encompasses array of tactics viz., genetic, cultural, mechanical, physical, legal, behavioral, biological and chemicals to be combined suitably to manage pests below the level of economic damage keeping in mind the socio economic and environmental safeguards of producers and consumers. Thus, IPM for a given crop or for a cropping and production system is knowledge intensive and variable. Under such circumstances, scope of information and communication technology (ICT) in plant protection in general and IPM in particular are multifold. India sustains IPM development and validation with crop-based institutes of Indian Council of Agricultural Research (ICAR) and State Agricultural Universities (SAUs) providing technical back up besides the Central Integrated Pest Management Centers established across all States anchoring its implementation. Since agriculture is a State subject the respective State Department of Agriculture is also actively involved in propagating IPM along with the provisions for supply of critical pest management inputs. Considering IPM is holistic and knowledge intensive, use of ICT is a must for an overall as well as precise crop health management fitting into the social milieu of farmers and consumers alike. The current write up describes the application of ICT in various areas of IPM with focus based on the work done with the involvement of ICAR-NCIPM, in general and under National Innovations in climate Resilient Agriculture, in particular.

Areas of Applications of ICT in IPM

Pest Diagnostics

Traditionally, crop inspection and plant disorders were identified by farmers or experts. However, it is not feasible continuously for the large fields. Nowadays artificial intelligence (AI) has begun to modify the plant protection environment around us. Computer vision empowered with machine learning promise to monitor crops for occurrence and diagnosis of disease at large scale. The four phases namely image acquisition, image pre-processing, features extraction, and classification are used in computer vision-based models. PLANTIX is a platform on mobile aids crop insect-disease diagnostics including India. DNA barcoding for easy and quick identification and high-throughput molecular methods such as polymerase chain reaction (PCR), species-specific primers, construction of phylogenetic tree to identify biotypes and possible origin are widely used in plant pest diagnosis. Common technologies associated with plant disease detection include fluorescence imaging, hyper spectral technique, GC-MS, enzymatic and antibody-based biosensors. Diagnosis of bacterial, fungal, and viral infections and insect damage attack in vegetables and fruits using volatile organic compounds emitted from plants is possible by electronic nose (*e*- nose) systems. Preparation of rapid precise diagnostic detection kits including artificial intelligence, environmental DNA (eDNA) technology coupled with isothermal nucleic acid amplification tests (iNAATs) including loop-mediated isothermal amplification (LAMP) are gaining importance. Sensor based gadgets for pest monitoring and management are feasible only through ICT. Automated trapping of insects and the data transfer to servers exist.

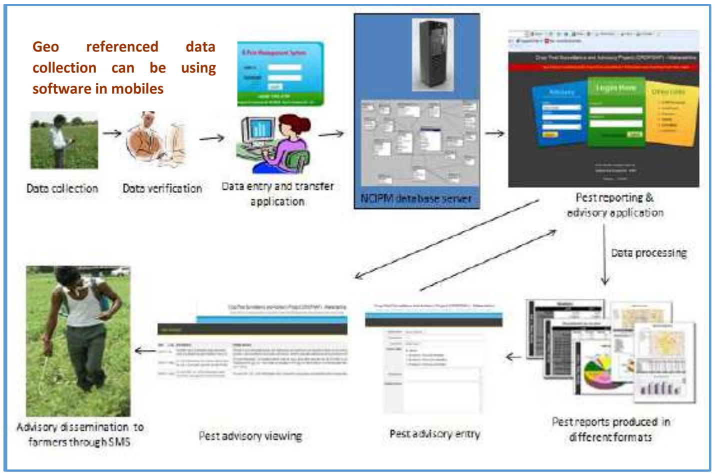
Real Time Pest Surveillance and Advisories for Field Level Pest Management

Pest surveillance is central to IPM and has components of survey and monitoring. Surveillance implies only observation and reporting of findings without intervention. Monitoring generally means to be aware of the state of a system and also refers to observation of change after there has been an intervention of some sort. Monitoring is the often used interchangeably with Surveillance. Pest surveillance is an official process of collecting and recording data on pest occurrence or absence by survey, abundance through monitoring or other procedures. Surveillance has components of survey and monitoring for use in: pest risk analyses, establishment of pest free areas, and the preparation of pest list. Surveillance is the need for (i) early detection of new pests esp. exotic pests for an emergency action resulting in measures of eradication or containment (2) for declarations of pest free areas involving detection, delimitation and monitoring of pest occurrence to select/establish pest free areas ,(3) to compile host and commodity pest lists and distribution records for categorization of pests and (4) making pest risk analysis and undertaking phytosanitary measures. Guidelines for pest surveys/surveillance and monitoring are a must using the direct and indirect tools/devices supported by services of rapid identity of pests, developing database and retrieval systems, and processing of information for needful trade, biosecurity and pest management and all need use of ICT.

The requisites for an ICT based pest surveillance include (i) an organized sampling plan for selection of fields, (ii) scientifically based sampling methodology for pests including the monitoring tools (GPS device, traps and lures for insects, data sheets (books), (iii) IT infrastructure (server, computers, customized software for data entry cum upload and reporting, and modems for internet connectivity),(iv) fixed schedule for pest surveillance, issue and dissemination of pest management advisories (based on ETLs) and (v) man power for pest observations, data entry and issue of advisories. Awareness creation among farmers and skill development for pest scouts/monitors and data entry operators provide strong foundation for e-pest surveillance (Vennila, 2016). There need to be continuous co-ordination among all the stakeholders right from programme formulation to field level implementation in terms of knowing the pest's status, recommendation of pest management advisories and their dissemination to farmers during each copping season. The repository of digital data base on pest scenario and their management on long term would empower the future generations with the insights of the past to plan for future. The ICAR based National Research Centre for IPM has been facilitating ICT as a vehicle for launching area wide IPM through e- pest surveillance *vide* its website: *https://ncipm.icar.gov.in/*. The ongoing programs *viz.,* (1) crop pest surveillance and advisory project (CROPSAP) (Maharashtra) across crops of Soybean, Cotton, Rice Pigeonpea, Chickpea, Maize, Sorghum and Sugarcane (*https://cropsap.maharashtra.gov.in/*); (2) horticulture pest surveillance and advisory project (HortSAP) (Maharashtra) (*https://ncipm.icar.gov.in/Horticulture/Default.aspx*) for the crops of Mango, Pomegranate, Banana, Nagpur mandarin, Sweet orange, Sapota, Tomato, Okra and Cashewnut stand as successful examples for large scale area wide implementation of IPM across Maharashtra. While CROPSAP engages mobileapps for collection of data from fields, HortSAP uses collection of data using data sheets, their entry into an offline software and online upload for pest status reporting. E-pest surveillance in horticultural crops in Haryana is another ICT based project implemented covering fruit and vegetable crops. CROPSAP & HORTSAP in Maharashtra, and E-pest surveillance in horticultural crops in Haryana together cover 24 crops from categories of cereals (three), pulses (two), commercial crops (two), oilseed (one), fruits (five), plantations (two) and vegetables (nine) and are implemented at the ground level. The flow chart shown depicts the ICT (internet) based surveillance system under implementation.

Framework of ICT based surveillance and advisory

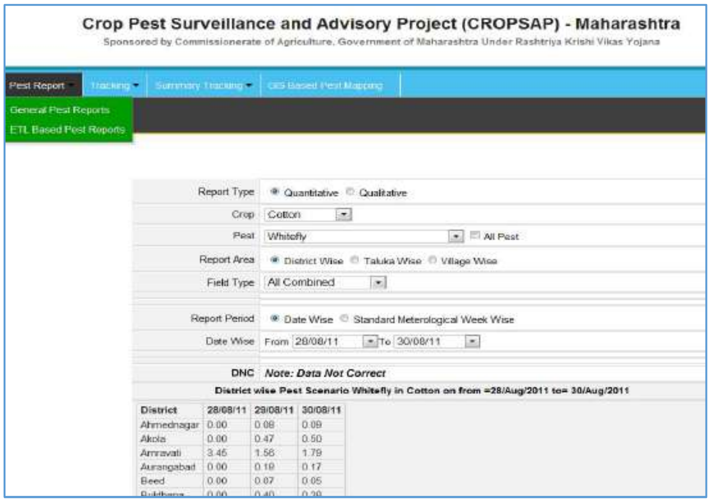
Different software components of have to be developed to acquire pest data from fields and to analyze the data for reporting of pest status in turn for issuing advisory for pest management using internet. In CROPSAP, a three tier architecture based system consisting of database for information storage; an offline application for pest data capture and data upload into database; an online application for pest reporting and advisory was developed. The different reports such as present and past pest situations can be viewed by experts. Data capture can be using data sheets and then entered into web based software, or substituting data collection with customized mobile apps developed for direct recording of field data and upload to server where reporting application exists. The state agri. universities issue advisory for different locations to the concerned state agencies for further spread it to the farmers.



Software development: The database was designed and developed for storage of interrelated pest information using SQL Sever 2000. The database consists of data fields to store data on various parameters. Various tables and views were created for different domain-specific information. Relationships were established among these tables for data normalization. Various stored procedures were generated in the database to execute different tasks.

Data entry & uploading module: Login details are created for data entry operators and pest monitors. The application is a standalone application for entry of details of fields, crop pests and other information. Data is uploaded after verification and subsequently transferred to centralized database through XML. Mobile apps directly transfers data to the server while in online.

Pest reporting & advisory module: The main purpose of pest reporting is to communicate immediate or potential danger. Immediate or potential danger normally arises from the occurrence, outbreak or spread of a pest. The provision of reliable and prompt pest reports confirms the operation of effective surveillance. Pest reporting allows necessary pest management requirements and actions to be taken. Pest reports contain information on the identity of the pest, location, pest status, and nature of the immediate or potential danger (near economic threshold level (ETL) or above ETL). Online application was developed using ASP.net technology as user interface which provides plant protection experts the reports for issuing advisories to different stake holders. System generates pest reports in different formats such as tabular, graphical or GIS maps. Both current as well as temporal pest reports are produced. The system has provision for producing pest reports for village(s)/taluka(s)/district(s) having pest(s) population above or equal to the pest ETL during selected dates that require/s attention of pest management experts. On the basis of pest situation of a particular location, pest experts feed the advisory (at taluk level) for state agencies to further spread it to the farmers for implement appropriate and timely decisions for pest management, if required.



Crop Pest Surveillance and Advisory Project (CROPSAP) - Maharashtra

Sponsored by Commissionerate of Agriculture, Government of Maharashtra Under Rashtriya Krishi Vikas Yojana

Report Type ● Quantitative ○ Qualitative
Crop Cotton
Pest Whitefly ☐ All Pest
Report Area ● District Wise ○ Taluka Wise ○ Village Wise
Field Type All Combined
Report Period ● Date Wise ○ Standard Meterological Week Wise
Date Wise From 28/08/11 To 30/08/11
DNC *Note: Data Not Correct*

District wise Pest Scenario Whitefly in Cotton on from =28/Aug/2011 to= 30/Aug/2011

District	28/08/11	29/08/11	30/08/11
Ahmednagar	0.00	0.08	0.09
Akola	0.00	0.47	0.50
Amravati	3.45	1.56	1.79
Aurangabad	0.00	0.19	0.17
Beed	0.00	0.07	0.05

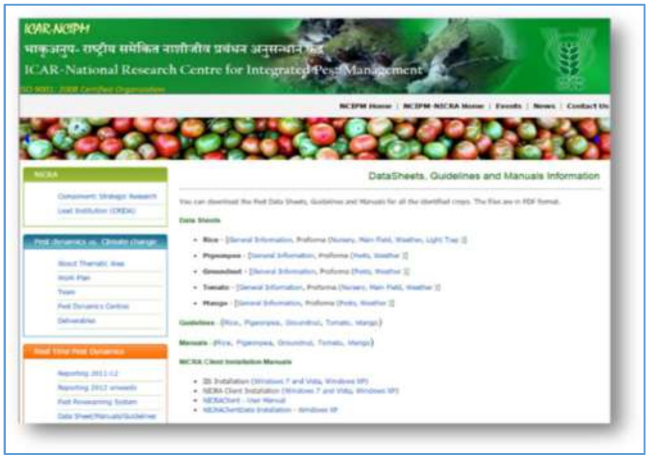
Electronic Solutions against Agricultural Pests (e-SAP) is an IT solution for crop health management designed and developed by University of Agricultural Sciences, Raichur (Prabhuraj, 2021). Over 2000 officers of both agriculture and horticulture are conducting pest surveillance cum advisory through e-SAP. At present e-SAP is supporting field user with 53 agricultural and horticultural crops capable of resolving over 1000 problems. The highlight of all programs is the digital delivery of the pest management advisories to the farmers as short message service (SMS). Third party evaluations of CROPSAP had worked out the cost (including cost of infrastructure and manpower) of Rs 10 per ha on a scale of 100 lakh ha since 2015 as against from Rs 16 per ha in 2010. Avoidance crop losses to a tune of Rs 1000 Cr/annum by spending a meager Rs 10 Cr. No outbreak of any of the major pests since 2009 but for pink bollworm in 2017, however reduced by 60% in 2018 over 2017. Thus, ICT based pest surveillance and issuing digital advisories for area wide popularization and implementation of IPM is a happening activity across states of Karnataka (e-SAP), Maharashtra (Vennila et al., 2016) and Haryana in India. Since Agriculture is a state subject there needs to be initiatives and importance given for real time pest surveillance-based management advisories wherein hand holding can be in collaboration central agencies.

Research Database Development and Analysis

All basic /strategic/ applied research involves the process of collecting and recording data on pest occurrence, their documentation, measurement of abundance using sampling plans and observation procedures and data analysis are all data driven and without ICT our know-hows would be limited. Since pest risks associated with climate change requires comprehensive and long-term data of crop pest-weather over space and time, ICT serves as a translational tool to assimilate data base effectively and efficiently. National Innovations in Climate Resilient Agriculture (NICRA) provided a research platform for studying changes in pest scenarios in response to climatic change across crops of rice, pigeonpea, groundnut and tomato wherein ICT was used as a tool for data base development on pests and weather through electronic networking of identified locations from different agro climatic zones of the country for the crops of rice, pigeonpea, groundnut and tomato.

Information System for *e* Pest Surveillance

All technical information essential for field pest surveillance (data sheets, guidelines and manuals) and the client software (set up and user manuals) constitute information system and are for ready reference all the time by anyone. Crop wise comprehensive standalone information system on 'Diagnosis and Sampling for Pest Surveillance (DSPS)' for rice, pigeonpea, groundnut and tomato have been developed as a window based application using *asp.net* with C# with descriptions and images of plant parts, insects, diseases and beneficial insects sampled *vis a vis* sampling procedures following the flow chart given below including the features of data sheets along with user manual incorporated. The application in respect of target crops is standalone (supplied through DVDs) and are also web hosted.

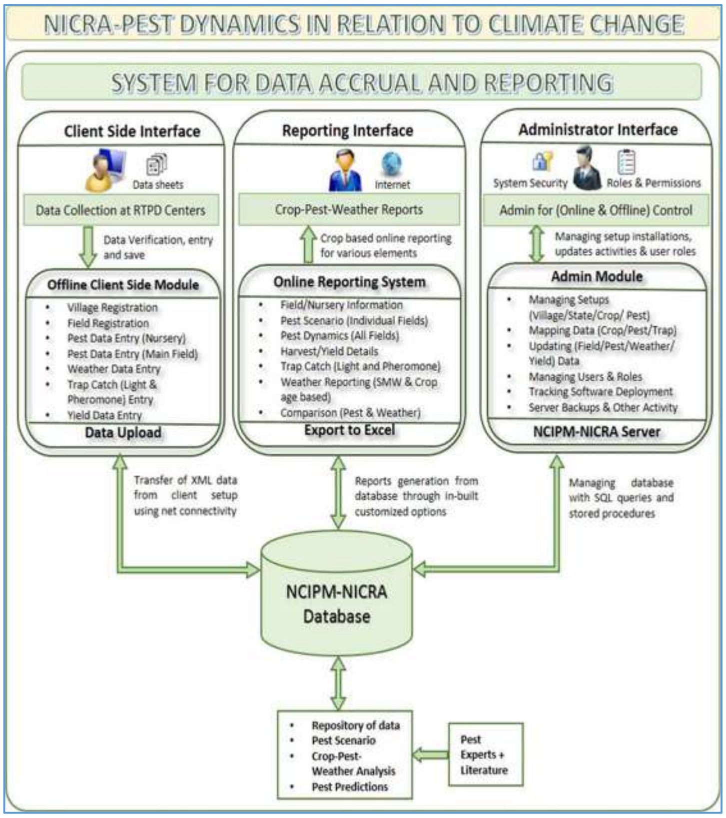


Data Accrual, Reporting and Analysis

An information and communication technology (ICT) (electronic-*e*) supported web-based pest surveillance system (*e- pest surveillance*) consisting centralized database, offline client data capture, admin panel, and data reporting and analysis was designed. Developed web application is working in two modules (1) Client and (2) Reporting applications integrated with each other to have user-friendly interface. Login page is created to provide authenticated user-based sessions for web application access. The credentials are system generated based on crop and study location. A separate console is developed for administrator to authenticate web application accessibility. Client software installations and problem solving are done through remote access using open source remote access software.

Software architecture:The architecture of client (for data accrual and upload) and reporting appilcations is presented hereunder.

Client application: Is XML based and installed in computer system of project co-opted centers to accrue information *viz.* field, crop, insect pest and disease details, weather observations, crop yields etc. All the relevant data of pest surveillance are collected by pest scouts and save/upload in client application by data entry operator. The application works in offline mode with uploads to the server database in online mode. Setup files for client software installation by RTPD centers are generated using admin panel configuring software applicable for the target surveillance center. NICRA client software user manuals were made available in addition to facilitating needful open source software such (window upgradations and team viewer for remote access between NCIPM and RTPDs for installation)



Reporting application: The reporting system has been developed to make available the details and data accrued through the pest surveillance from the fields and received at the server through uploads from the client-side application. Reporting application consisting admin panel is functional and available on website: *https://ncipm.icar.gov.in* . Reporting systems for 2011 and later from 2012 onwards were developed and hosted due to mid-course modification in data sheets. Reporting modules have options to retrieve data sets in the desired formats and units that could serve researchers to work on various ecological models analyzing within/ between field variations, multispecies associations, and yield loss assessment by crop pests besides crop-pest-weather/climatic analysis across seasons or locations. Data stored in the server database are used further for viewing and downloading different customized reports in online mode *viz.,* (1) Crop pest weather reporting; (2) Comparison [weather, light and pheromone traps and pest scenario across locations] and (3) Spatial [pest-weather (graphical)]. The queries serve as data provider for Web applications from SQL server. Experts make queries and analyze data for intra and inter-center pest dynamics. These optimized reports can be exported to MS excel for display and printing purposes.

Sensor based and Geospatial Technologies

Recent technologies of internet of things (IoT) are all ICT based. A wireless sensor network is a system comprised of radio frequency (RF) transceivers, sensors, microcontrollers and power sources. Wireless sensor networks with self-organizing, self-configuring, self-diagnosing and self-healing capabilities have been developed to solve problems or to enable applications that traditional technologies could not address. The wireless sensors are cheap enough for wide spread deployment in the form of a mesh network and also it offers robust communication through redundant propagation paths. The low-cost, low-power small devices equipped with limited sensing, data processing and wireless communication capabilities perfectly suits precision agriculture where decisions are to be made at micro-climatic level at right time/place/input crop-weather-pest/disease relations using wireless sensory and field-level surveillance data on closely related and interdependent pest (Thrips) – disease (Bud Necrosis) dynamics of groundnut (peanut) crop. Various data mining techniques were used to turn the data into useful information/ knowledge/ relations/ trends and correlation of crop-weather-pest/disease continuum. These dynamics obtained from the data mining techniques and trained through mathematical models were validated with corresponding ground level surveillance data. It was found that Bud Necrosis viral disease infection is strongly influenced by Humidity, Maximum Temperature, prolonged duration of leaf wetness, age of the crop and propelled by a carrier pest. All the latest facilities relating to climate change studies on crops/pests under controlled conditions (have essentially digital components and provide understanding climate change impacts on specific pests of target crops. Open top chambers (OTP), carbon di oxide chambers, Free-Air Carbon Dioxide Enrichment (FACE), Free-Air Temperature Enrichment (FATE) and Carbon Dioxide Temperature Gradient Chamber (CTGC) are all ICT embedded tools. Results of controlled studies are useful to understand future pest status through use of process-based phenology models when combined with projected climatic scenarios.

Information and communication technology aided geo-spatial techniques such as remote sensing can be taken advantage for surveillance and quick monitoring in larger areas. The associated technological tools associated are hyper spectral imaging at ground as well as airborne devices including drones. here is an opportunity to make increased application of ICT, geo-spatial and simulation techniques, and artificial intelligence (AI) for pest surveillance, diagnostics and forewarning. GIS tools also can be applied - hot spots can be identified; and pest risk maps can be generated using models to focus our attention on pest management. Global Positioning Systems (GPS), a system of radio-emitting and receiving satellites used for determining positions on the earth is a great tool for supporting plant health programs for data visualization/query, survey data collection, management, and analysis, risk and pathway analysis and change detection, and the possibilities are endless! Geospatial technology includes typical GIS software packages such as ArcGIS, ArcExplorer, MapPoint and Google Earth. Use of remote sensing, collecting and interpreting information about the environment from a distance using satellite imagery, radar, or aerial photography has been demonstrated for insect pests. Remote sensing application for the area wide assessment of mealybug severity in Warangal (AP), and of damage at Sirsa (HR) on cotton (Prabhakar *et al.,* 2012; Prasad *et al.,* 2014) are recent examples in India.

Pest Forewarning

The sophisticated tools of ICT allows us to build a quality database and that various approaches from basic heuristics to application of artificial intelligence for development of pest predictions can give models for field use emphasis was laid to develop software products of pest forecasting. Forewarning is an essential component of IPM, and predicting of pest incidence based on changing climate is a challenge as its impact on pests is both direct and indirect. e-pest surveillance done under CROPSAP and NICRA has sustained and widened the scope of forewarning. Given the broad range of forecasting methods, rule-based predictions have served as simple but robust tools of forewarning of rice insect pest severity amongst seven locations viz., Ludhiana (Punjab), Chinsurah (West Bengal), Raipur (Chhattisgarh), Karjat (Maharashtra), Hyderabad (Telangana), Mandya (Karnataka) and Aduthurai (Tamil Nadu) besides maximum severity of *Spodoptera litura* for groundnut cropping system at Dharwad (Karnataka) and early blight of tomato at Bengaluru (Karnataka). Empirical models using field incidence/severity of insect pests and diseases of rice, pigeonpea, groundnut and tomato for various locations with their respective weather patterns have been validated to be effective for designated periods of crop season. Such empirical models and the rule-based models have been facilitated for validation as well as field use through web hosting as well as application for use through web and smart phones (available on Goggle play store).

IPM Dissemination

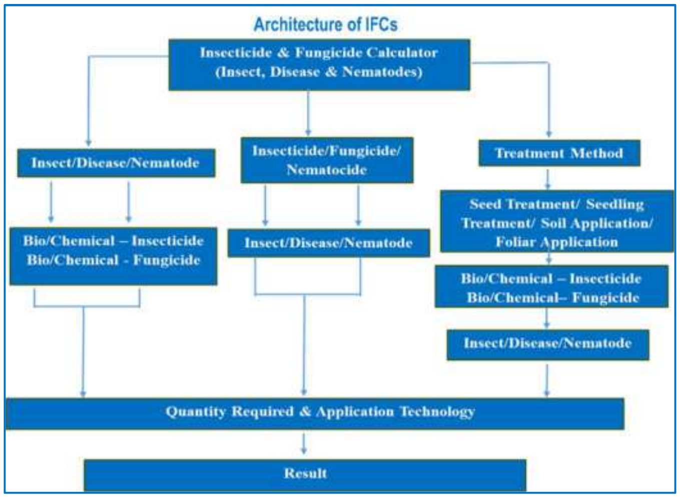
Recent advancements of digital tools are largely mobile based as mobiles have become part and parcel of daily lives of mankind. Android smart phones as a communication tools are popular and that people of different fields including pesticide dealers, extension functionaries and farmers possess and use them in their daily lives. Customised applications for need-based use in plant protection are potential value additions in the digital era. The innovations described here have been the successful application of digital technologies for facilitating scientific knowledge resources to aid in operational decision making and as tools of dissemination for pest management at farm level.

Mobile Apps on Pest Prediction

PESTPREDICT, an android mobile application for pest forewarning assists researchers, extension personnel of agriculture and farmers to get location specific forecasts of desired insect pest(s) or disease(s) for their effective management on target crops. PESTPREDICT reduces calculation efforts and provides an instant and extempore framework for use of developed prediction models. While success of predictions can be continuously improved through refinements considering the changing pest scenario and climate, immediate requirement is the need for locations of target crops to use the application on regular basis and issue 'pest alerts' at times prediction of 'high' severity levels. Web enabled/mobile application-based predictions are specific to locations and insects, creating awareness amongst potential users including extension functionaries is of utmost importance. QR codes generated to facilitate easy and instant downloads for use of the application are furnished hereunder. It is always pertinent to have a 'pest alert' backed up by direct and random field level monitoring.

Mobile Apps on Insecticide and Fungicide Calculations

Ever since the green revolution of 1960s in India, crop protection has relied largely on use of ever-growing pesticides with various modes of action and the visual effects of pest management using synthetic chemicals were obvious and attractive to farmers. Over time, use of pesticides with their indiscriminate and injudicious use including the use of banned and spurious ones led to harmful effects of resistance build up by pests leading to their field control failures, pesticide poisoning of humans and natural resources, residues in food and food chains in addition to growers getting caught in debt traps leading to farmer suicides. More than 290 pesticides have been registered in India by the Central Insecticide Board and Registration Committee of the Department of Plant Protection, Quarantine and Storage of Government of India. It is imperative to use pesticides with label claims at recommended dosages using proper application technologies for effective pest management. One of the greatest limitations towards judicious use of pesticides is the lack of adequate awareness on the different groups of pesticides registered and their dosages specific to pests recommended for use on different crops in addition to their method of field application. As many chemicals are available for use against a single insect or disease and their dosages differ in respect of crops, it is difficult to remember all details by researchers, students, extension personnel, pesticide dealers and farmers. Making available mobile apps to facilitate scientific pesticide use on major crops is of potential value addition and hence mobile apps were developed for insecticide and fungicide calculations.



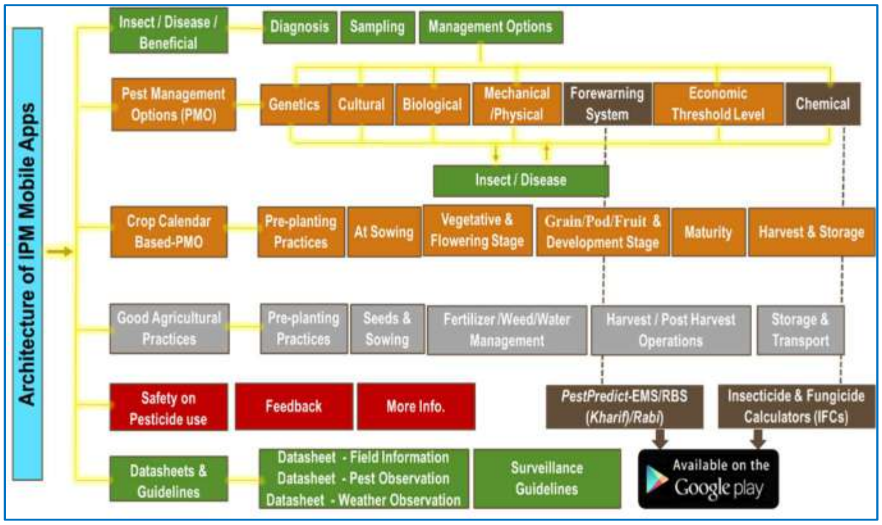
Considering the current status and recommendation pathways of pesticide use in India and the potential outreach of digital technology, android applications were developed for insecticide and fungicide calculations (IFC). IFCs in respect of sixteen crops viz,, Rice, Cotton, Chillies, Tomato, Brinjal, Okra, Groundnut, Cabbage, Wheat, Pigeonpea, Potato, Soybean, Chickpea, Cauliflower, Mustard and Sugarcane that have chemical and biological insecticides/ fungicides/nematicides together numbering 119, 87, 88, 83, 57, 43, 37, 39, 31, 32, 20, 44, 34, 20, 14,12 and 13 against insects, diseases & nematodes totaling 27, 17, 19, 23,16, 13, 20, 12, 31, seven, six, 21, six, 12, 10 and 13, respectively have been developed and hosted. IFC architecture includes scenarios for selecting insect pest/disease/nematode or pesticides (chemical/biological) or methods of application (seed/seedling treatment, soil application, and foliar spray) to proceed for further calculations. All IFCs have been developed using an open source software 'SQLite' on the framework of android studio. IFCs assist in calculation of pesticide quantity required to be procured for a given farm area besides facilitating dilution and method of their application. All insecticides and fungicides included have 'label claims' for use on specific crops complying with recommendations of Central Insecticide Board and Registration Committee. Feature of 'area converter' providing conversions of area to desired standard units, 'More info' displaying details on source and contact information besides and 'demo' on "how to use IFCs" are made available. 'Feedback' feature allows users to interact with developer of IFCs. Maize Pesticide Calculator (Maize-PC) is similar to IFCs in architecture but has additional features of selecting for weeds, herbicides associated and treatment methods indicating options of whorl application, poison baiting and pre or post emergence applications. Maize-PC covers 22, 11 and 14 insecticides, fungicides and herbicides for management of four insects, 11 diseases and 27 weeds, respectively. While the IFCs of Rice, Cotton, Soybean, Pigeonpea and Chickpea and Maize-PC are bilingual (English & Marathi), Groundnut, Tomato, Brinjal, Cabbage, Potato and Sugarcane-Wheat & Mustard are in English. Cauliflower and Okra IFCs are in English and Hindi. Chilli IFC

(English) has been updated with two more (Kannada & Tamil) languages. All the apps are available on to Google Play Store.

Mobile Apps on IPM

Management of pests at field level is done through integration of different tactics and technologies that are compatible, altogether referred as integrated pest management (IPM) to achieve an economically profitable and environmentally safe food production system with safety of humans from occupational and food residue hazards due to pesticides. IPM is a strategy that integrates genetic, cultural, biological, mechanical, physical, and chemical methods of pest management each having a variety of options to choose from based upon considerations of space and time driven by socio cultural economic milieu of crop growers and market demands and hence holistic.

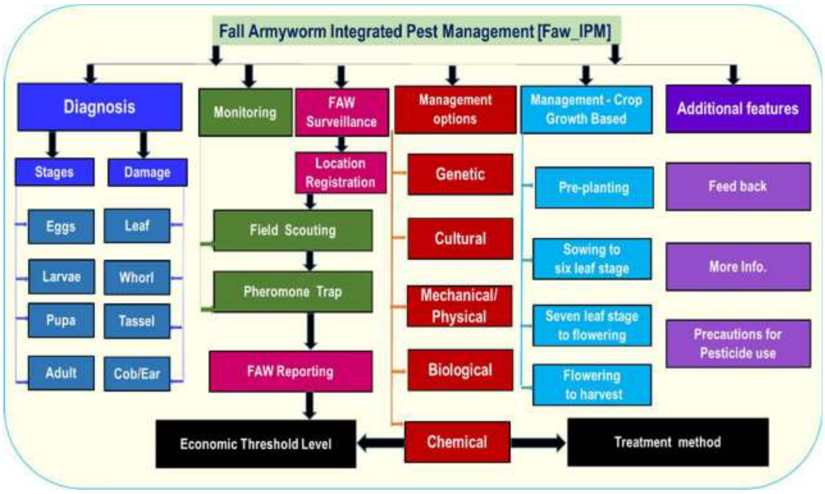
Mobile Apps on Crop based IPM: IPM mobile apps have been developed for crops of Rice, Pigeonpea, Groundnut and Tomato based on information assembled from recommended package of practices of different States and crop/pest specific reports and web portals of Agricultural Universities of different states. Architecture of IPM apps were designed after requirement analysis for clients. IPM apps used open source and lightweight database namely 'SQLite' that works on eclipse android 23.0.1 framework using .db format. Java Core Library provided most functions of the app and Dalvik virtual machine was used for specific improvements at backend. specific reports and web portals. Architecture of IPM apps were designed after requirement analysis of the clients as given in the flow diagram below. Provisions of accessing other apps viz., IFCs and forecast apps 'Pestpredict' within IPM apps in respect of crops have been made.



IPM apps allow the users to know information as per requirement in different ways as listed hereunder.

- Selection of an independent option of pest management followed by further options relating to specific pest (insect/disease) through drop down menu.
- Feature of ‘crop calendar-based pest management’ provides details of management options pertaining to stages of crop growth.
- Details on good agricultural practices (GAP) covering essential agronomic practices including weed, fertilizer and water management besides operations at pre-sowing, harvest and post-harvest stages of crop production.
- Additional information on ‘safety on pesticide use’ and ‘data sheets and guidelines’ for pest surveillance have been integrated.
- External standalone apps on forewarning using empirical model and rule based model systems of insects and diseases *viz., Pestpredict* EMS (*kharif*), *Pestpredict* EMS (*rabi*) and *Pestpredict* RBS and insecticide and fungicide calculators that guide right selection of pesticide for a given pest at right dosage with calculations and narratives on field application methods are linked appropriately under desired features in respect of target crops. All mobile apps on crop IPM are in English, and are standalone occupying a memory size of 10-12 MB. All work in offline subsequent to initial installation through Google Play Store.

Mobile app on FAW-IPM: Development and deployment of an android mobile app for the invasive insect of fall armyworm IPM (Faw_ipm) has been a step towards nationwide knowledge creation cum dissemination of FAW management in maize. Eleven cultural, five mechanical, 16 natural bio agents (nine parasitoids, three predators & four pathogens), two monitoring methods, six applied bio control options (one botanical, an egg parasitoid & four microbials) and eight chemical insecticides (one seed treatment & seven foliar) and economic thresholds of one moth/trap/night and plant damage 5,10 and 20% constitute FAW IPM. Faw_ipm was built on the architecture as given in the flow chart below using open source SQLite database engine in android studio frame work. The app allows the user to identify four stages of FAW and damage to four parts of the plant either using keys for diagnosis or based on images along four stages of crop growth. Monitoring using pheromone traps with installation guidelines and field scouting using sampling procedure with option FAW surveillance to register locations, fields and dates are available with reporting of calculations on moths/trap/week and per cent plant damage, respectively. All options under ETL based management have calculations on quantity of biologicals/chemicals to be procured for a given farm area based on their recommended dosages, dilutions with water, method of field application and waiting periods as applicable. Selection of management along crop growth stages offer three, 18, five and two options in respect of pre-planting, sowing to six leaf stage, seven leaf to flowering , flowering to harvest, respectively. Additional features *viz.,* 'Feedback' allowing users to interact with developers, 'More info' furnishing details on developers and source of information and 'Precautions on pesticide use' are available. Current version of 'Faw_IPM' is in English and Marathi uploaded on Google Play Store and is also accessible for downloads at: *https://ncipm.icar.gov.in/Web_cropsap/AndroidApp.htm*. The android based mobile app (Faw_IPM) is a drive towards digital IPM that gives real time information access to researchers, crop protection specialists, pesticide dealers, extension functionaries and maize growing farmers of India on FAW management. Faw_IPM also propels the dissemination and adoption of scientifically proven and effective methods of FAW management at a quicker pace across maize growing areas (Vennila *et al.,* 2021)



ALL MOBIE APPS ON IFC AND IPM ARE DISSEMINATION PRODUCTS WITHIN THE FRAMEWORK OF 'DIGITAL INDIA' FOR EFFECTIVE CROP PROTECTION IN INDIA. WAY FORWARD FOR A BETTER OUTREACH OF MOBILE APPS WOULD BE THEIR CONVERSION TO ALL POSSIBLE LOCAL LANGUAGES OF DIFFERENT INDIAN STATES ALONG WITH EFFORTS ON THEIR POPULARIZATION.

GET IT ON Google Play

Conclusion

IPM is an evolving system approach that accommodates all need-based innovations, concepts and policies in each area of pest management tactic right from pest resistant crops, ecological engineering, augmentative biocontrol, semiochemicals and pesticides with varied modes of action. While the role of chemical pesticides cannot be denied within IPM, their judicious use is far from satisfactory due to a variety of reasons resulting in occupational and pollution hazards in addition to pesticide residues in food and water. Enormous inventions and innovations in the area of crop protection requires integration of ICT paving way for precise methods, formulations/ materials, and technologies in crop health management. Like any other digital tools, ICT based applications for pest management needs creation of awareness on their availability with purpose to all the stakeholders related to crop protection for its wider utility. The possible convergence with department personnel, extension officials and other stakeholders of plant protection certainly would improve its applicability. While the ICT based pest surveillance for data base development and assessment of pest scenario would pay short as well as long-term dividends for crop protection research and development, available customized ICT tools on IPM are highly field oriented and farmer centric applications. All applications help to take informed and instant decisions on status and management of pests on target crops and are products for dissemination of crop protection technologies under IPM umbrella within the framework of 'Digital India'.

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Use of Semio-chemicals and Pheromones in Insect Pest Management (IPM)

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Introduction

The term Semio-chemicals is derived from a Greek word 'someone' meaning a mark or a signal. Semio-chemicals are signalling chemicals used to carry information between living organisms and which cause changes in their behaviour (Dicke and Sabelis, 1988). These are employed both for intra-and interspecific communication systems. The compounds, which convey information between members of the same species, are known as pheromones and if the message is inter-specific, the compounds are known as allelochemicals. Allelochemicals can be divided into signals that benefit the receiver (kairomones), the emitter (allomones), or both (synomones) (Nordlund et al., 1981). Insects use semio-chemicals to locate mate, host, or food source, avoid competition, escape natural enemies, and overcome natural defense systems of their hosts. Semio-chemicals play an important role in host-parasitoid relationship, which was categorized by into three stages: habitat-location, host-location and host-acceptance, and oviposition (Rutledge, 1996).

Pheromones: A pheromone is a secreted or excreted chemical factor that triggers a social response in members of the same species. Pheromones are chemicals capable of acting outside the body of the secreting individual to impact the behavior of the receiving individual. The term "pheromone" was introduced by Peter Karlson and Martin Lüscher in 1959, based on the Greek word pherein (to transport) and hormone (to stimulate). They are also sometimes classified as ecto-hormones. These chemical messengers are transported outside of the body and result in a direct developmental effect on hormone levels or behavioural change.

Insect pheromones are volatile organic molecules of low molecular weight that elicit a behavioural response from individuals of the same species and can be used to communicate between members of the same or the opposite sex (Phillips, 1997). The amount of pheromones that insects release is extremely low and varies from a few nanograms to micrograms per unit of time, depending on the species (Piñero and Ruiz-Montiel, 2012). The characterization of the silk moth sex pheromone (E, Z)-10,12-hexadecadien-1-ol (Butenandt et al., 1959), which is released by the female silkworm moth, *Bombyx mori* (Lepidoptera: Bombycidae) to attract mates, opened doors to the establishment of chemical ecology as a scientific discipline (Heuskin et al., 2011).

Pheromones are of 2 types

1. Releaser effect pheromones: These produce an immediate and reversible behavioural change in the receiving insects. They operate through the olfactory sensillae.
2. Primer effect pheromones: These trigger a chain of physiological changes in the body of the insect and operate through gustatory sensillae. These regulate caste determination and reproduction in social insects.

Types of releaser effect pheromones

1. Sex pheromones 2. Aggregation pheromones 3. Alarm pheromones 4. Trail pheromones

1. Sex pheromones: Many insect species release sex pheromones to attract a mate, and these are well studied in many lepidopterans (moths and butterflies). Bombykol is the first sex pheromone isolated and identified from silkworm, *Bombyx mori* in 1959 by A. Butenandt and co-workers. Important sex pheromones which have a potential in pest management are disparlure (gypsy moth), gossyplure (pink bollworm), grandlure (cotton grey weevil), looplure (*Trichoplusia ni*) Helilure (*Helicoverpa armigera*) and Litlure (*Spodoptera litura*). Sex pheromones of *Earias vittella*, *E. insulana*, *Pectinophora gossypiella* etc., are also used in pest management.
2. Aggregation pheromones: These pheromones induce aggregation or congregation of insects for protection, reproduction and feeding. They also function in defense against predators, mate selection, and overcoming host resistance by mass attack. For example, some species of coleopteran pests produce aggregation pheromones, which are equally attractive to both sexes and thereby provide an opportunity to reduce the local population as a whole. Examples include the bark beetles, *Ips* spp. and *Dendroctonus* spp. (Byers et al., 1990) and boll weevil, *Anthonomus grandis*, the palm weevils, *Rhynchophorus* spp. (Rochat et al., 1991) and banana weevil, *Cosmopolites sordidus* (Dryophthoridae) (Beauhaire et al., 1995).
3. Alarm pheromones: These are primarily an antipredator device, a warning to conspecific about the presence or attack of an enemy. This warning elicits different behaviour such as dispersion or escape in different insects. Ex: Terpenes (Aphids), aldehydes (Hemipterans), formic acid (Ants) and monoterpene hydrocarbons (Termtie soldiers).
4. Trail pheromone : These are used to find mates, or to utilize food resources more efficiently. Ex: Caproic acid (Zootermopsis sp.), hexanoic acid and heptanoic acids (Ants)

Allelochemicals: A substance that is significant to organisms of a species different from its source, for reasons other than food.

Different types of allelochemicals are

a) Allomone: A compound released by one organism which evokes a reaction in an individual of a different species that is favourable to the emitter but not to the receiver. Ex: Citral which is a mandibular secretion of many ants and bees acts as a defensive allomone for ants and an attractant for bees.

b) Kairomone: A compound released by one organism which evokes a response beneficial to receiver but not to the emitter. Ex: Male sex pheromone of bug, *Nezara viridula* acts as an attractant to its parasite, the tachnid fly, *Trichopoda pennepes*

c) Synomone: A substance released by organism which benefits both the sender and the receiver.

d) Antimone: A substance produced or aquired by an organsim that when it contacts an individual of another species in the natural context, evokes in the receiver a behaviour or physiological reactions that is maladaptive to both emitter and the receiver.

e) Apneumone: A chemical released by nonliving substance that is beneficial to the receiver but detrimental to other organism in the substance.

Uses of pheromones in insect pest management

Sex pheromones are used in 2 ways I. Population survey II. Behaviour manipulation I.

1. Population survey: Synthetic sex pheromones of a large number of insect pests are used to know the population density in an area. This will help • To know whether the pest population level has reached ETL for making pest management decisions • To know the time of pest build up and the correct time for the adoption of control measures • To know the suitable mode of control

II. Behaviour manipulation

The two strategies available to manipulate insect behaviour are

1. Stimulation of normal approach response

2. Disruption of chemical communication

1. Stimulation of normal approach response: The normal response of an insect to sex pheromone is attraction. This attraction is used to kill the insects in the following ways a) Use of pheromone baited traps: Pheromone baited traps are placed at suitable

points. When the pests have gathered in large number they can be killed by insecticides. This technique is also called as male annihilation technique. b) Orientation to a source of chemo-sterilant or insecticide : By the use of pheromones, the insects could be guided to a sources of chemo-sterilant or insecticides to be sterilized or get killed. c) Orientation to a combination of light and pheromone: Pheromone and light are together used to attract a large number of nocturnal insects. The large number of males attracted can be killed by insecticides.

2. Disruption of chemical communication: Synthetic pheromones are introduced in the environment to mask the natural pheromone and this disrupt the normal pheromonal communication between pest species. This will result in failure to locate their mates and there by prevent mating.

In pest management pheromones are used for various purposes such as

1. Monitoring 2. Mass trapping 3. Mating disruption

1. **Monitoring**: Pheromone baited traps are used to detect both the presence and density of the pest species. Insect populations can thus be estimated and new areas of infestation can be detected at a very early stage. The trap catches are correlated with weather parameters to develop forewarning models. One of the most widespread and successful practical applications of semio-chemicals is in detection and monitoring of pest populations (Witzgall et al., 2010). Currently, pheromone lures are used in traps to monitor many different crop pest species (Witzgall et al., 2010). Such monitoring systems allow farmers to time insecticide applications, which reduces economic and environmental costs of insecticide application.

2. **Mass trapping:** Mass trapping is an extension of the use of species-specific semio-chemical baited monitoring traps, with the aim of reducing or eradicating populations of target pests by capturing as many individuals as possible. The lure can be a synthetic pheromone, a food or host attractant, or a combination of the two, which is sufficiently effective when deployed in an optimally efficient trap design at a suitable density to suppress the pest and reduce economic damage to the target crop. To achieve this, traps have to capture a large proportion of the population in an area, before mating or oviposition, and retain or kill captured individuals. The lure must be more effective than natural sources of attraction such as mates or food/oviposition sites and ideally retain efficacy over the entire period of adult insect reproductive activity to reduce damage to a minimum.

Mass trapping is more effective if the targets pest being small or isolated populations with low immigration rates, univoltine species or those with a limited life cycle, host range or flight period (El-Sayed et al., 2006). In Lepidoptera, species-specific female produced sex pheromones are used to attract only males. Due to the males' capacity for multiple matings, a very large proportion of the male population is removed thus female fecundity is reduced.

3. **Mating disruption**: Pheromones are used for suppressing mating by confusing male insects. Mating disruption aims to disrupt chemical communication by organisms and interrupt normal mating behaviour by dispensing synthetic sex pheromone, thereby affecting the organism's chance of reproduction (Cardé and Minks, 1995). Mating disruption techniques is commonly used for the management of gypsy moth (*Lymantria dispar*) in North American forests, the codling moth (*Cydia pomonella*) in apple and pear trees worldwide and the grapevine moth (*Lobesia botrana*) in grape in the European Union and Chile (Witzgall et al., 2010). In India mating disruption technique is used for the management of pink bollworm (*Pectiphora gossypiella*) in cotton by using PB Rope L dispensers @ 200 / ha

Advantages and Limitations of Pheromones

Advantages

- Pheromones are non - pollutant and hence ecologically acceptable
- Minute quantities of pheromones are required to attract and kill a large number of insects and hence they are economical
- Pheromones are species specific and hence pose no hazards to non-target organisms
- Pheromones offer an easy means to monitor the buildup of pest populations
- This is a labour saving method since a large number of insects are brought from long distances right at the doorstep for being destroyed

Limitations

- Sex pheromones can attract only one sex and the other sex could still be there to cause damage • Most sex pheromones attract only adults while the larval stage causes the damage • Pheromones are known for only a very few species of insect pests
- This method demands knowledge and expertise which are not within the reach of most of the farmers
- Quick results cannot be obtained with pheromones and hence they are not suitable as short-term control measures •

Involves high cost to synthesize

Potential use of semio-chemicals in pest management

Insect sex pheromones are the semio-chemicals that are widely used for the management of insect pest particularly members of the order Lepidoptera. Aggregation pheromones from the order Coleoptera are also used for the management of agricultural insect pests of economic importance.

Attract and kill (A&K): The technique as the name implies simply use an attractant or semio-chemical to lure an insect to a point source that contains a killing agent (insecticide, pathogen, or sterilant), hence the technique is termed attract and kill, attract and infect, and attract and sterilize, respectively. The technique leads to the reduction of the insect population by killing the target insect or reducing its fitness and fecundity or disabling it by causing disease.

Volatile kairomones from food or host plant sources hare used alone, or in combination with pheromones, to trap both male and female pests in search of food or oviposition sites are used to control dipteran and some coleopteran species (El-Sayed et al., 2009). The banana weevil, C. sordidus, was controlled by mass trapping using baits made from host plant pseudostems (Alpizar et al., 2012). Food odours including hydrolysed proteinaceous baits were developed to trap a wide range of tephritid fruit fly species and used in lure and kill strategies. The natural product, methyl eugenol (4-allyl-1,2-dimethoxybenzene), which is a male pheromone precursor extremely attractive to males of the genus *Bactrocera*, has been used in IPM programmes (Witzgall et al., 2010). Parapheromones, e.g. Trimedlure, Ceralure, some plant volatiles, and essential oils (Cunningham et al., 1990; El-Sayed et al., 2009) are widely to control fruit flies, including male Mediterranean fruit fly, *Ceratitis capitate*. The use of sex pheromone lures for monitoring (M), mass trapping (MT) and mating disruption (MD) and use of semiochemicals for the management of insect pests by mass trapping (MT) and attract-and-kill (AK) is given in Table 1 and 2 respectively.

Push-pull strategy: Cook et al. (2007) defined the push-pull strategy as the use of semio-chemicals to make a protected resource an attractive or unsuitable for the pests (push) while luring them to an attractive source (pull) where the pests can be removed. Push–pull technology is a strategy for controlling agricultural pests by using repellent "push" plants and trap "pull" plants. For example, cereal crops like maize or sorghum are often infested by stem borers. Grasses planted around the perimeter of the crop attract and trap the pests, whereas other plants, like *Desmodium*, planted between the rows of maize repel the pests and control the parasitic plant *Striga*.

Table 1: Use of sex pheromone lures for monitoring (M), mass trapping (MT) and mating disruption (MD)

Insect pest	**Pheromone Use**
Agricultural crops	
Yellow rice stem borer, *Scirpophaga incertulas*	M, MT, MD
Groundnut leafminer, *Aproaerema modicella*	
Leaf folder, *Cnaphalocrocis medinalis*	M
Maize stalk borer, *Chilo partellus*	M
Tomato leafminer, *Tuta absoluta*	M, MT
Brinjal fruit and shoot borer *Leucinodes orbonalis*	MT
Fall armyworm, *Spodoptera frugiperda*	MT

Pink bollworm, *Pectinophora gossypiella*	M, MD
American bollworm, *Helicoverpa armigera*	M, MT
Tobacco caterpillar, *Spodoptera litura*	M, MT
Cotton boll weevil, *Anthonomus grandis*	M, MT
Spotted bollworm, *Earias vittella*	M, MT
Horticultural crops	
Potato tuber moth, *Phthorimaea operculella*	M, MT
Sweet potato weevil, *Cylas formicarius*	M, MT
Gypsy moth, *Lymantria dispar*	M
Codling moth, *Cydia pomonella*	M
Stored products Cigarette beetle, *Lasioderma serricorne*	M, MT
Indian meal moth, *Plodia interpunctella*	M, MT

Table 2: Use of other semio-chemicals for the management of insect pests by mass trapping (MT) and attract-and-kill (AK)

Species	Lure	Purpose
Mediterranean fruit fly, *Ceratitis capitata*	Trimedlure	MT
Melon fly, *Bactrocera cucurbitae*	Cue-lure	AK
Oriental fruit fly, *Bactrocera dorsalis*	Methyl eugenol	AK
Corn rootworm, *Diabrotica* spp.	Kairomone	AK
American bollworm, *Helicoverpa armigera*	Kairomone	AK

Conclusion

Pheromones and other behaviour-modifying semio-chemicals are now an integral part of numerous pest management programmes and are expected to play an important role in crop protection of the future. Semio-chemicals have great potential to provide alternative solutions, because they are relatively non-toxic to vertebrates and to beneficial insects, are generally used in small amounts, and are often species-specific. These will help provide a sustainable and environmentally friendly replacement to the broad-spectrum insecticides, either as monitoring or management tools of critical IPM programmes. The main application of semio-chemicals in IPM has been in pest monitoring systems where semio-chemicals are used as attractive baits to lure insects into traps. Achieving reductions in pest populations with semio-chemicals has been more challenging. The ultimate challenge will be to increase the adoption of pheromone-based pest management technologies by making them cost-effective and easily available to the farmers. The future research should focus on the use of multiple pheromones to monitor several pests simultaneously, and use of pheromones for behavioural manipulation of natural enemies.

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Role of Low External Input IPM in rainfed crops

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Introduction

Crop production in rainfed regions is by nature dependent on monsoon behaviour and is therefore highly risky. Rainfed regions are also highly heterogeneous in terms of land terrain, soil productivity, climate and socio-economic conditions, all of which influence the crop productivity. Another important factor that affects crop production is the incidence of pests and diseases. Considering the poor capacity of the farmers to invest on plant protection measures, the incidence of pests and diseases often leads to significant losses of productivity and income to the farmers. Thus, there is considerable scope to develop a system that is diverse and less prone to pests and diseases (Risch, 1983). When other pest management technologies are superimposed on such systems, it becomes much easier and cheaper for the farmer to manage the pests rather than in monocultures which are more prone to pest incidence and require considerable investments in pest management. Low External Input Integrated Pest Management (LEIIPM) seeks to optimize the use of local available resources by combining the different components of farming system which is the major crux of Low External Input for Sustainable Agriculture (LEISA).

In recent years, the value of low external inputs and traditional techniques, including non-chemical alternatives, have been increasingly urged. These are viewed as technology options that could help create sustainable systems and decrease or avoid the needs for expensive and undesirable chemical inputs. There is a need for investment in low external input and non-chemical alternatives that include farmer empowerment. In agriculture, the fight against harmful organisms is essential, and it is therefore necessary to develop appropriate technologies to regulate and control pests. Environmentally-friendly, biological options that do make use of preparation of plant-based pesticides on the farm do exist. These options are based on natural crop protection approaches that make use of the diversity found in nature itself. Many countries have initiated IPM programme and due emphasis is given to Low external input IPM as a part of LEISA. Experiments were conducted to find out whether it is possible to have Low external input IPM measures as modules for the control of insect pests of pigeonpea. A range of treatments cultural, mechanical, crude extracts and different ITK techniques which are proven to be effective were identified and integrated as IPM modules and evaluated in terms of pest control and economics. It was expected that to provide usable cost-effective pest control package, which in turn can be used for organic farming also.

Options of LEIIPM

LEIIPM has two major principles which are akin to cultural control of insect pests. It has been defined as the tactful use of regular farm practices to delay or reduce insect pest attack. This involves the manipulation of the environment to make the 'less favourable' for insect pests and 'more favourable' for crop growth. Pest control is sought through a reduction in initial colonization of the pest, a reduction in reproduction and survival and an increased dispersal from the system. It is cost effective and ecologically safe approach in pest management. Researchers have examined how manipulation of various practices like time of sowing, tillage crop rotation, intercropping etc. are helpful in managing the pests through LEIIPM.

Time of sowing

The crop sowing should be done in such a way that its most susceptible growth stages coincide with time when the pest is least abundant and minimizing the damage. Sowing immediately with onset of monsoon is effective in the control of shoot fly and stem borers in sorghum. Incidence of groundnut bud necrosis and sesamum phyllody were found to be low in early sown crops.

Pod borer incidence on pigeonpea was reported to be less when the crop was sown simultaneously by all the farmers. This is because the pest is distributed over a larger area (in the same phase of life cycle) reducing the intensity of the pest. Also, it should be seen that varieties of same duration are sown in given area so that pest inoculums is not carried over to the long duration varieties from the short duration. Synchronized sowing is recommended to avoid pest distribution for long time.

Tillage

Reduction of population of insect pests and carry over to the next crop could be achieved with off seasonal tillage or summer ploughings. Ploughing after harvest is a cultural practice known to destroy stubble, weeds and other vegetation, which serve as alternate hosts of insect pests. Tillage exposes the insect (larval and pupal stages) to their natural enemies, predators (birds) and to adverse climatic factors such as high temperatures and low humidity besides causing physical damage to insect. Tillage especially after harvest minimized the incidence of stem borer in sorghum; root grubs in groundnut and also pod borers in pigeonpea crops.

Crop rotation

The rotation of crops is essentially a means of maintaining soil fertility so that an appropriate sequence of crops used in a rotation can produce better average yields than continuous cultivation of the same crop (mono cropping). At the same time crop rotation is also helpful in reducing pest infestation. This is achieved when dissimilar crops are rotated to interrupt continuity of food chain of pests with a narrow range of hosts. For e.g. rotation with sorghum and groundnut reduces important insect pests (Sorghum stem borer and groundnut leaf miner). Obviously crop rotation is most effective against pest species that have a narrow host range and limited range of dispersal.

Crop-crop diversity

Crop diversification and rotation are essential elements of LEIIPM. Diversification can enhance economic stability by allowing the risks of production agriculture to be spread over a greater number of crops. Ideally, the crop mix should be complementary in nature.

Pest pressures may be reduced in diversified systems for various reasons, most important being the encouragement of beneficial insect diversity and abundance and reduced ability of pests to locate their preferred feed. Providing already diversified growers with an additional benefit from combining certain crops should be a valuable contribution. Several studies indicated that diversification practices such as intercropping are beneficial because of lower damage by insect pests in these systems (Risch *et al*., 1983).

Significance of Intercropping

The crop diversity is of several ways like crop-weed diversity, crop-border diversity and crop-crop diversity. By introduction of one crop in existing crop, crop-crop diversity can be created or enhanced (Baliddawa 1985). Intercropping is the most popular form of crop-crop diversity.

Biotic, structural, chemical and micro climatic factors apparently constitute associational resistance, which probably reduce the pest infestation. The general reduction of pest infestation was noted in early reviews on intercropping (Srinivasa Rao *et al*., 2002). The factors that influenced pest; population in intercropping might be physical protection from wind, shading, prevention of dispersal, production of adverse stimuli, olfactory stimuli camouflaged by main crop, presence of natural enemies and availability of food. Research in diversified agro-ecosystem demonstrated that these systems tend to support less herbivores load than corresponding monoculture. However, the generalization that diversity decreases the pest problems does not hold true for many types of situations and pests. Similarly, the intercropped system may not necessarily reduce pest density nor do increase yield.

The growth behavior of pigeonpea makes it less competitive for resources when grown with other short season crops. Availability of cultivars with different durations of maturity offers scope for manipulation of crop environment for low pest incidence (in terms of choice of appropriate duration and intercrop). The impact of duration and intercropping on insect pests and natural enemies was well documented (Srinivasa Rao *et al.*, 2003). It is therefore important to identify an effective combination of non-chemical measures, evaluation of their efficacy and development management strategy for LEIIPM. The significant effect of intercropping on various insect pests across different crops was mentioned by Srinivasa Rao (2007) and observed that in majority of the systems reduction of pest and proliferation of natural enemies was noticed across different field crops.

Intercropping

A method was evaluated for the selection of vegetable crops suitable for intercropping and compatible pest management. The method tested was based upon ecological principles that predict the diversified systems should be less prone to attach by pests, owing to reduced ability of pest insects to locate their preferred food plants and enhanced activity of beneficial insects. The results showed that intercropping per se increased beneficial insect diversity. Largely certain crops determined abundance of pest insects e.g., broccoli, which attracted large number of crucifer flea beetles. Diversifying plots resulted in improved natural enemy complexes. Litterick *et al.*, (2002) opined that pest control strategies in LEIIPM are mainly preventive rather than curative. The balance and management of cropped and uncropped areas, crop species and variety choice and the temporal and spatial pattern of the crop rotations used all aim to maintain a diverse population of beneficial organisms including competitors, parasites and predators of pests

Cover crops for diversification

Cover crops can be beneficial for intensive agricultural production in a number of ways. Water penetration and infiltration can be improved by root growth of a cover crop and by returning organic matter to soils. Increased organic matter may improve the soils ability to retain moisture. If leguminous cover crops are grown, soil nitrogen can be increased through nitrogen fixation (Venkateswarlu *et al.*, 2005). Grasses are particularly helpful in promoting soil structure and soil aggregating stability because of their fibrous root systems. Microbial activity, often stimulated by cover crop root exudates and organic matter additions to soils, has also been shown to promote aggregate stability. As microbes decompose organic matter, nutrients are released. Weed suppression for subsequent crops may be another benefit. Furthermore, cover crops can provide a favourable environment to attract and sustain beneficial arthropods. Ngouajio and McGiffen (2004) evaluated the effect of cover crops and management systems on weed and insect populations in lettuce (*Lactuca sativa*). Cover crops treatments included cowpea (*Vigna unguiculata*), sudangrass (Sorghum bicolor), and the traditional summer dry fallow. Over the two years, cover crops had no effect on insect populations in lettuce, as neither cover crop is an alternate host for lettuce insect pests. However, the population of cabbage loopers [(Tricoplusia ni (Hubner)] increased at the end of each growing season in cowpea mulch plots. The cowpea cover crop suppressed weeds and increased yield. The integrated system reduced production inputs. The number insecticide applications was reduced from four to one without an increase in insect damage. Cowpea cover crop offered many advantages in vegetable based cropping systems. Additional crops were often included in a grower's operation for greater diversification. It was suggested to maintain insectary plantings in or near fields to provide a habitat and food source for beneficial arthropods.

Trap crop

Crops that attract pests away the main crop have potential for the crop production. If the alternate crop (trap crop) is maintained in vigorous state, the pest may never even leave the trap crop. If the pest population builds up and begins to leave the trap crop, the trap crop can be mowed or sprayed to prevent damage to main crop. The trap crop can also serve as an additional reservoir of beneficial predators and parasites. The main crop seldom needs insecticidal treatment. There are most successful cases of use of Indian mustard and African marigold as trap crops against diamond back moth, *Plutella xylostella* in cabbage and tomato fruit borer *Helicoverpa armigera* in tomato. Crop such as alfalfa is used in organic production of strawberries and cotton in abroad. Use of trap crops like okra, canabinus, marigold, castor, early pigeonpea, coriander, maize are recommended for south and central India. However, in North zone okra should not be used as trap crop and cotton should not be grown in and around citrus orchards to avoid the spread of CLCV disease.

Biorationals

The final rule states that farmers may use some naturally occurring chemical controls as a last resort. Organic chemical controls include 'biorational' pesticides that are derived from natural sources, particle film barriers, botanical pesticides made from plants, and compost teas. Products derived from neem tree are one of the important components of non-pesticidal approach which have proven their efficacy under field conditions and are now being routinely adopted by the farmers. Use of neem in pest management can be considered as one of the best examples of LEISA and if successfully adopted can be a role model for the so-called 'alternate agriculture'. The main advantages of neem-based products are: i. Available locally in the villages or on the farmer's fields, ii. The technology of preparation of extracts and application is fairly simple which the ordinary farmers can adopt easily, iii. Neem products are renewable, viz., available every year, iv. Neem products do not leave residues in the environment, i.e. soil, groundwater and food products like grain, vegetables and fruits. They are relatively safe to the natural enemies and birds.

Recommended uses of Neem products at the farm level

Following are some recommended uses of neem products at the farm level. These practices can be adopted by the farmers with least external inputs and are based on extensive research during the last one decade in India and abroad. The methods of preparation were given as suggested by Venkateswarlu and Srinivasa Rao (2006).

Aqueous Neem Seed Kernel Extracts (NSKE)

This is prepared by mixing 5% finely ground powder / paste of well dried neem seeds in water. The seed powder is tied in a cloth, immersed in water over-night and stirred well to make a ready to spray suspension. The suspension need to be filtered through a double layered cloth while filling the sprayer. The main advantage of the suspension is its effectiveness since it is prepared freshly and the drawback is that it cannot be stored for long since it is water extract. Farmers need to collect neem fruits well ahead of the cropping season, depulp and dry them under shade. Moisture control in the depulped seeds is critical in maintaining the quantity of the active ingredient. Drying seeds upto a moisture content of 8% is recommended for short term storage.

Use of Neem Oil

Neem oil is mixed in water at 0.5 to 2% concentration, emulsified well and sprayed on the crop. Adding soap solution (5 ml/litre) or a commercial emulsifier is important as spraying of neem oil alone or oil not properly mixed with the water can damage the crop due to the phytotoxicity. The quality of neem oil is very important. The active ingredients in neem oil like azadirachtin and salanin remain stable only upto 65°C. Therefore, oil expelled from cold expellers where the temperature is regulated during expelling is most effective. Farmers can also use hand expelled oil without any loss of active ingredients. Because of the variation in the quality of neem oil used by the farmers, the effectiveness of the product differs from place to place.

Use of Neem Cake

Neem cake is used for soil amendment @ 0.25 to 0.5 t/ha and it has variety of effects such as control of nematodes, soil borne fungi and as nitrification inhibitor. Unlike kernel extracts and neem oil, which can be used against specific crop pests more effectively, neem cake can be used for a variety of crops to and fruit trees to achieve multiple benefits of increased nitrogen use efficiency and control of soil borne pests and diseases.

Other plant products

Like neem, pongamia and custard apple are other plant species with good potential in IPM and LEIIPM. Pongamia seed powder extracts, oil and cake can be used in similar manner as that of neem. Combined use of neem and pongamia oil in 5:1 ratio was found to be more effective than neem oil alone. custard apple leaf extracts and seed extracts are also quite effective. Leaf extracts are prepared by grinding 50g fresh leaves in one litre or boiling in water till dark colour is obtained. Cooled extract is filtered and sprayed. In case of seed extracts 500g powder can be suspended in 10 litres. After 12h soaking, it is ready for spray.

Other options

Bird perches

Keeping 3-4’ bamboo stakes in fields is effective as bird perches to invite insectivorous birds against tobacco caterpillar in groundnut, semilooper in castor and gram caterpillar in pigeonpea. Sometimes trap crop of sunflower in groundnut crop also acts as bird perch. Farmers that produce with organic methods reduce risk of poor yields by promoting biodiversity. Common game birds such as the ring-necked pheasant and the northern bobwhite often reside in agriculture landscapes, and are a natural capital yielded from high demands of recreational hunting. Because bird species richness and population are typically higher on organic farm systems, promoting biodiversity (predators and birds) and can be seen as logical and economical.

Mulching

Adoption of suitable mulches with either sorghum straw or glyricidia retains the moisture and decreases the infestation of termites.

Control of Queen termite

The Queen termite creates the colony by laying eggs and tending to the colony until enough workers and nymphs are produced to care for the colony. She can live for more than ten years and produce hundreds to eight six thousand of eggs per day. Colonies can have several million termites with the help of chemical means is difficult. Collection and destruction of queen termite is the only way to control the termites.

Conclusions

LEIIPM is a production system that sustains the health of soils, ecosystems and people. It relies on ecological processes, biodiversity and cycles adapted to local conditions, rather than the use of inputs with adverse effects. It combines tradition, innovation and science to benefit the shared environment and promote fair relationships and a good quality of life for all involved. This is the philosophy of LEISA and the above-mentioned various options of pest control can be used as per the availability and convenience and crop aimed. The principle of LEIIPM is akin to non-pesticidal approaches of pest management. The protection and conservation of natural enemies is central core of LEIIPM and can be achieved through habitat management and biodiversity. Species found in most LEIIPM provides a means of agricultural sustainability by reducing amount of human input (e.g. fertilizers, pesticides).

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Vulnerability and risk assessment of climate change

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Introduction

Climate change has emerged as a potent threat to sustainability of food security and agriculture. The Coupled Model Inter-comparison Project (CMIP) 5 projections for India show that the average climate is likely to be warmer by 1.7 to 2.0^0 C for 2030s and by 3.3 – 4.8^0 C for 2080s compared to the pre-industrial times. The precipitation is likely to increase by 5 to 6 per cent and 6 to 14 per cent, for 2030s and 2080, respectively. Agriculture, being a biological production process, is obviously affected by climate and hence the projected change in climate will have implications to sustainability of agricultural production and of livelihoods of those dependent on agriculture. Indian agriculture, dominated by small holders with low adaptive capacity, is vulnerable to adverse impacts of climate change. Intensified adaptation efforts are needed in spite of the Paris Agreement arrived at COP 21 to limit warming to 1.5^{0}C. Adaptation requires resources in terms of investments and interventions. However, considering climate and climate change are spatially variable, not all regions are equally impacted by climate change and vary with their capacities to adapt and shocks to adapt to. A well planned and better targeted adaptation is critical to building resilience to agriculture and to farmers' livelihoods. Assessment of risk and vulnerability informs policy and programme planning towards this. Since district is the basic unit of administration in India, risk and vulnerability assessment at the district level will be of more policy relevance. This policy brief presents the summary of such district level assessment of risk and vulnerability to climate change as detailed in Rama Rao *et al*., (2019).

Vulnerability – meaning and concepts

'Vulnerability' has emerged as a cross-cutting multidisciplinary theme of research in the current context, characterized by rapid changes in environmental, economic and social systems (O'Brien et al., 2004). The dictionary meaning of the word 'vulnerable' means propensity to be harmed. However, the word vulnerability has been used and vulnerability was assessed without actually being defined in many different contexts. Vulnerability is an *ex ante* concept in that what is likely to happen in future is the focus of analysis and thus the analysis has to lead to making decisions as to what is to be done in the present. Further, vulnerability of *what* to *what* are to be clearly defined along with the preference criteria for evaluation (Ionescu et al., 2009).

Vulnerability and its assessment received attention in three important areas of research: disaster management, economic development and climate change. The disaster management literature sees vulnerability as susceptibility to a climatic disaster and is often concerned with the location of the system or entity. On the other hand, the vulnerability research in the broader area of economic development is concerned with vulnerability to, poverty for example, wherein the interest is to assess whether or not an economic decision making unit becomes worse off (in terms of outcomes) in the event of a climatic or non-climatic shock given its characteristics. Vulnerability is viewed both as a component of poverty as well as a determinant of poverty in the literature on poverty.

Vulnerability is sometimes seen as a threshold value or tipping point which can be described as a degree of acceptable damage (Joakim et al., 2015). The shifting of the threshold or tipping points is seen as the responses to moderate or deal with vulnerability. Though there is a vast literature on the theoretical development in the conceptualization and analysis of vulnerability, this discussion is limited to vulnerability and assessment in the context of climate change only.

Evolution of vulnerability assessment

Vulnerability assessment is generally done in a number of different contexts and in view of different stakeholders. However, three important contexts for vulnerability assessment can be identified. These three contexts have different goals, varying information needs and thus will lead to different policy implications. These three contexts are related to fixing long term mitigation targets, identification of vulnerable regions for providing international assistance and for recommending adaptation measures for different regions or sectors. The evolution of vulnerability assessment in terms of focus, frameworks and methods broadly reflect these three decision contexts. The assessments concerned with mitigation aspects focus on biophysical impacts of climate change and are usually referred to as impact assessments. Following such impact assessments are the first and second generation vulnerability assessments that increasingly recognized the importance of non-climatic factors in determining vulnerability. These vulnerability assessments are then followed by what are referred to as adaptation policy assessments whose purpose is to identify adaptation strategies and are more policy oriented. These assessments clearly recognize the 'facilitation' and 'implementing' aspects of both mitigation and adaptation and differentiate between adaptive capacity and adaptation. The key characteristics of these four broad classes of vulnerability assessment are summarized in table 1.

Table: Key features of different stages of climate change vulnerability assessments

	Impact Assessment	**First Generation VA**	**Second generation VA**	**Adaptation Policy Assessment**
Focus	Mitigation policy	Mitigation policy	International assistance	Adaptation policy
Analytical approach	Positive	Mainly positive	Mainly positive	Normative
Main result	Potential impacts	Pre-adaptation vulnerability	Post-adaptation vulnerability	Adaptation strategies
Time horizon	Long term	Long term	Mid to long term	Short to long term
Consideration of non-climatic factors	Little	Partial	Full	Full
Integration of natural and social sciences	Low	Low to medium	Medium to high	High
Stakeholder consultation	Low	Low	Medium	High
Typical question	What are biophysical impacts of CC?	What socioeconomic impacts are likely to result from CC?	How vulnerable are systems or entities to CC after after feasible adaptation?	What adaptation options can be recommended to reduce vulnerability?

Source: Fussel and Klein (2006)

Approaches to vulnerability assessment

'Outcome vulnerability is conceptualized as 'end point' analysis where in the impact of climate change is examined on productivity or production of a particular crop or animal species either through simulation modeling or through physical experimentation. This is also referred to as biophysical impact assessment or first-generation vulnerability assessment. Such assessments 'superimpose future climate scenarios on an otherwise constant world to estimate the potential impacts of anthropogenic climate change on a climate-sensitive system' (Fussel and Klein, 2006). The emphasis gradually shifted to derive policy lessons from vulnerability assessment as the purpose of such assessment was to identify strategies that reduce vulnerability of the systems or populations concerned.

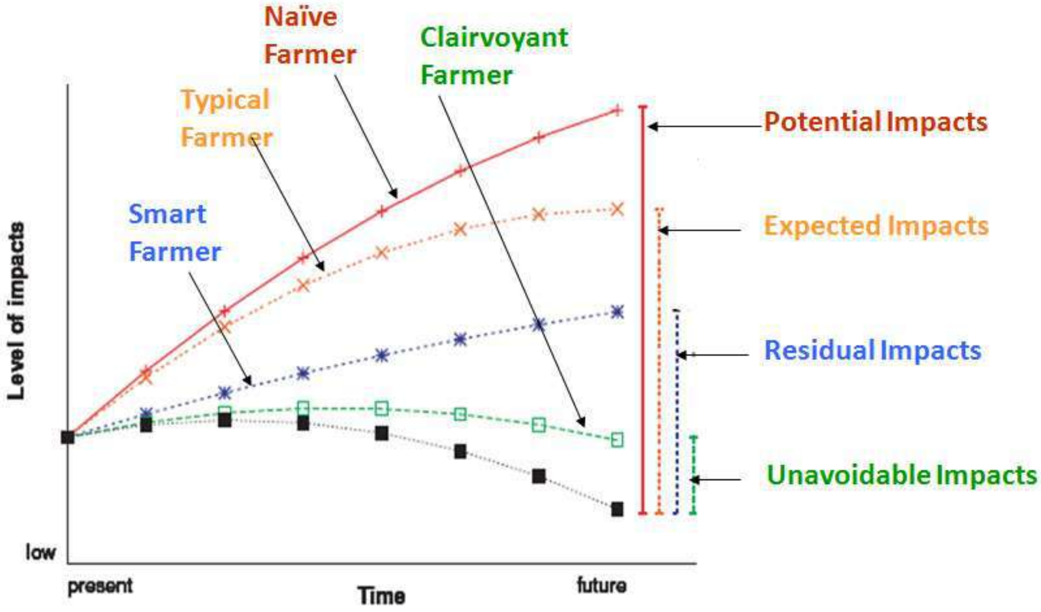
The socio-economic approach to vulnerability assessment proposes that the attributes of the system or entity of interest predispose it to the adverse impacts of an external shock (climate change or variability) (Adger and Kelly, 1999) and thus it is referred to as 'starting point analysis'. In this case, vulnerability is regarded as a pre-existing condition (Alexandra Jurgilvech et al., 2017) in terms of health, education, wealth, etc. of the individuals and the differential endowments of individuals are responsible for varying vulnerability.

The integrated approach combines both these approaches integrating bio-physical and socio-economic dimensions of vulnerability. As the vulnerability assessments evolved, more non-climatic data became a part of such assessments.

Current vulnerability analyses the current risks to the system of interest whereas *future vulnerability* assessments are concerned with future risks. Vulnerability assessment is considered static or dynamic whether the temporal changes in the predisposing conditions and/or risk are considered in the analysis.

Conceptualization of impacts and vulnerability

Figure 1 depicts hypothetical trajectories for the level of climate-related impacts (caused by anthropogenic climate change as well as natural variability) on a climate-sensitive system. The lowest trajectory denotes the (unrealistic) reference case of an undisturbed climate where variations in the level of impacts over time are solely caused by changes in non-climatic factors. The illustrative trajectory shows an initial increase in climate-related impacts (e.g., due to population growth) followed by a substantial decrease later (e.g., due to economic development). The other trajectories present the impacts associated with a single climate change scenario for four different assumptions regarding adaptation. They include (in descending order of impacts) the 'dumb farmer', who does not react to changing climate conditions at all; the 'typical farmer', who adjusts management practices in reaction to persistent climate changes only; the 'smart farmer', who uses available information on expected climate conditions to adjust to them proactively; and the 'clairvoyant farmer', who has perfect foresight of future climate conditions and faces no restrictions in implementing adaptation measures. Depending on the level of adaptation assumed, assessment results may fall anywhere in the range spanned by the 'dumb farmer' and the 'clairvoyant farmer' trajectories in Figure.



Conceptualization of impacts and vulnerability (Source: Fussel and Kelin, 2006)

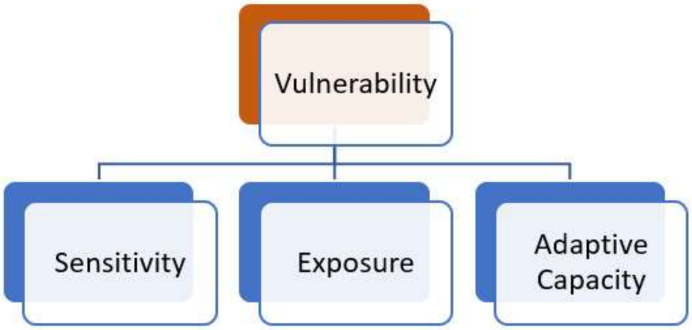
The IPCC-AR4 framework of vulnerability assessment

There were a plethora of studies on climate change vulnerability starting in 2000s as the national governments and international community are increasingly concerned about dealing with climate change. Though there are varying conceptualizations and definitions of vulnerability in the context of climate change, the one given by the IPCC is adopted in a large number of studies (Schneider et al., 2007). IPCC in its 3rd and 4th Assessment Reports define vulnerability a "The degree to which a system is susceptible to, or unable to cope with, adverse effects of climate change, including climate variability and extremes. Vulnerability is a function of the character, magnitude, and rate of climate variation to which a system is exposed, its sensitivity, and its adaptive capacity" (McCarthy et al., 2001, 2001, 2007). This conceptualization views vulnerability as a residual impact of climate change: the sensitivity and exposure together determine the potential impact which will be moderated by adaptation. Adaptation is the manifestation of adaptive capacity.

Sensitivity is defined as "the degree to which a system is affected, either adversely or beneficially, by climate-related stimuli". It is determined by demographic and environmental conditions of the region concerned. Exposure is defined as "the nature and degree to which a system is exposed to significant climatic variations". Thus, exposure relates to climate stress upon a particular unit of analysis (Gbetibouo and Ringler 2009). "A more complete measure of exposure to future climate change would require consideration of projected changes in climate in each analysis unit" (Eriyagama et al., 2012). Adaptive capacity is "the ability of a system to adjust to climate change, including climate variability and extremes, to moderate potential damages, to take advantage of opportunities, or to cope with the consequences. It is considered to be “a function of wealth, technology, education, information, skills, infrastructure, access to resources, stability and management capabilities” (McCarthy et al., 2001).

In this framework, adaptive capacity is largely consistent with socioeconomic approach and sensitivity with biophysical approach and both are internal dimensions. The component of exposure is viewed as an external dimension. While higher exposure and sensitivity mean higher vulnerability, higher adaptive capacity implies lower vulnerability and hence is inversely related to vulnerability. Although lack of standard methods for combining the biophysical and socioeconomic dimensions is a limitation to this approach, it can be helpful in making policy decisions (Deressa et al., 2008).

This definition and framework of vulnerability is depicted in Figure.



Components of vulnerability

Change of vulnerability assessment framework by IPCC with AR-5

The literature on vulnerability and its assessment is continually evolving drawing on works in different fields. The dynamic trait of vulnerability and its components is not adequately addressed in the Third and Fourth Assessment Reports of the IPCC. The recent literature suggests that the risks due to climate change are also a result of complex interactions among social and ecological systems and the hazards arising out of climate change rather than being externally generated alone. Various facets of these interactions have to be carefully differentiated to understand risk to inform policy making for risk management. The AR 5 framework (Fig 3) emphasizes these aspects as well as that the very components of vulnerability and risk will also interact with the contextual factors of development pathways and the climate systems (Oppenheimer, et al., 2014). Also, inclusion of 'exposure' as a component of vulnerability as in AR 4framework, may trigger decisions that may potentially lead to maladaptation given the uncertainty associated with climate projections.

Vulnerability – a component of risk assessment

The AR5 proposes a different framework where in vulnerability is placed as one of the determinants of risk, the other two being 'exposure' and 'hazard'. The definitions given by AR 5 for risk and its components (Oppenheimer, et al., 2014) are given below:

Exposure: The presence of people, livelihoods, species or ecosystems, environmental functions, services, and resources, infrastructure, or economic, social, or cultural assets in places and settings that could be adversely affected.

Vulnerability: The propensity or predisposition to be adversely affected. Vulnerability encompasses a variety of concepts and elements including sensitivity or susceptibility to harm and lack of capacity to cope and adapt.

A broad set of factors such as wealth, social status, and gender determine vulnerability and exposure to climate-related risk.

Impacts: (Consequences, Outcomes) Effects on natural and human systems. In this report, the term impacts is used primarily to refer to the effects on natural and human systems of extreme weather and climate events and of climate change. Impacts generally refer to effects on lives, livelihoods, health, ecosystems, economies, societies, cultures, services, and infrastructure due to the interaction of

climate changes or hazardous climate events occurring within a specific time period and the vulnerability of an exposed society or system. Impacts are also referred to as consequences and outcomes. The impacts of climate change on geophysical systems, including floods, droughts, and sea level rise, are a subset of impacts called physical impacts.

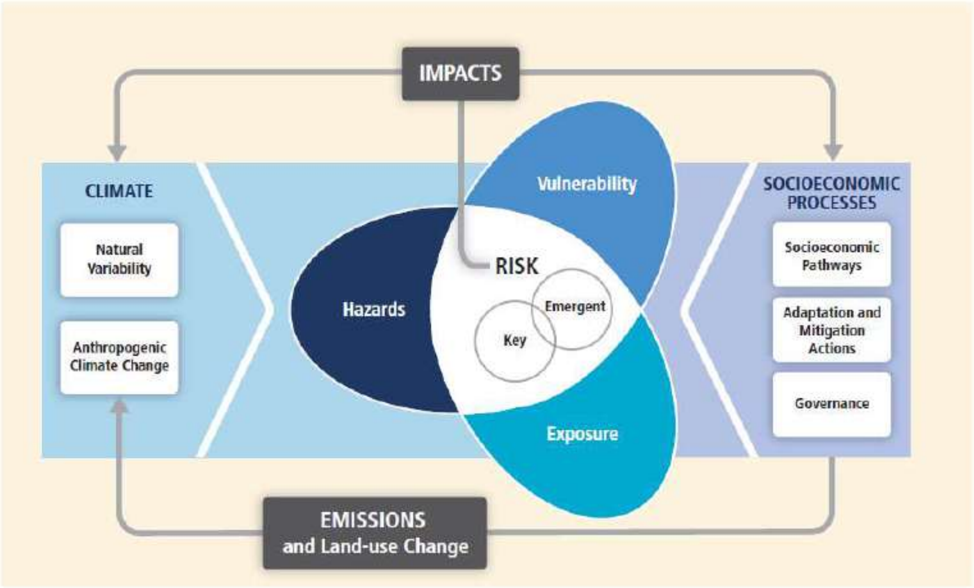
Hazard: The potential occurrence of a natural or human-induced physical event or trend or physical impact that may cause loss of life, injury, or other health impacts, as well as damage and loss to property, infrastructure, livelihoods, service provision, ecosystems, and environmental resources. In this report, the term hazard usually refers to climate-related physical events or trends or their physical impacts.

Risk: The potential for consequences where something of value is at stake and where the outcome is uncertain, recognizing the diversity of values. Risk is often represented as probability of occurrence of hazardous events or trends multiplied by the impacts if these events or trends occur.

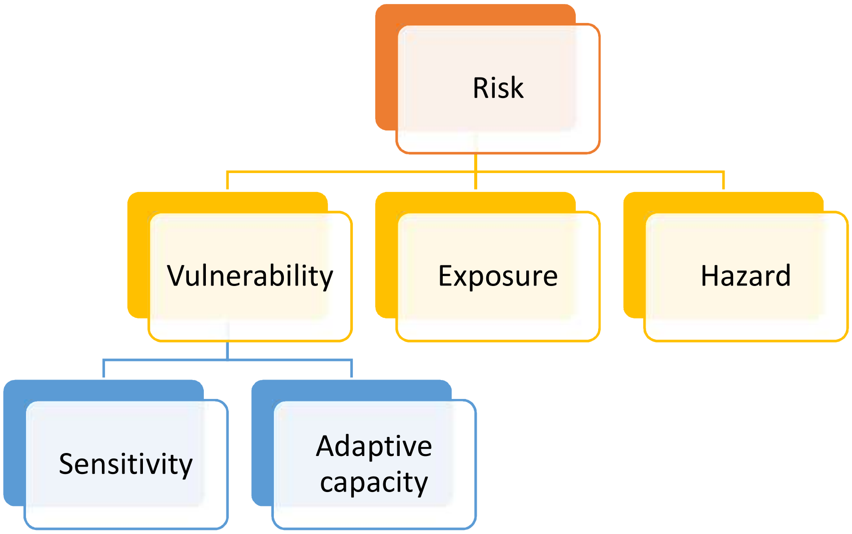
Risk = (Probability of Events or Trends) × Consequences

Risk results from the interaction of vulnerability, exposure, and hazard.

The AR4 and AR5 definitions and frameworks view the terms vulnerability and exposure differently. Exposure in the AR 4 terminology is related to climate related shocks that a system is exposed to whereas the AR 5 describes it being related to the individuals, systems, etc. being exposed to the 'hazard' which is a concept introduced in AR 5 framework. Vulnerability, as per AR5, is more a predisposition to an external shock and whether it will lead to risk depends on whether the vulnerable system is located (exposure) in a place where the 'hazards' are likely to occur. Thus, a highly vulnerable system may not suffer risk due to climate change or a less vulnerable system may face risk if it is placed where severe hazard incidence is possible. Thus, the relationship between these three components of risk are more explicit and policy relevant. The AR5 vulnerability framework is closer to the disaster management conceptualization which is considered more appropriate in the context of climate change.



Framework of vulnerability and risk (Source: Oppenheimer et al., 2016)



Dimensions of risk and vulnerability

The AR5 risk conceptualization furthers the risk analysis by identifying two kinds of risk: key risks and emergent risks. Key risks are potentially severe consequences arising when systems with high vulnerability interact with severe hazards. Different criteria are suggested to categorize a risk as key which are based on the magnitude of the risk, high vulnerability of a particular group of population, criticality of the sector in the economy. Emergent risks are those that are not direct consequences of climate change hazard but are results of responses to climate change. For example, migration of population from a region due to climate change related hazards may increase the vulnerability and thus risk of receiving regions; similarly increased groundwater extraction during a drought may increase the vulnerability and risk in future. Thus, emergent risks are a result of spatial linkages and temporal dynamics related to responses to changing climate.

Thus AR5 framework places more emphasis on identifying and managing risk and thus views vulnerability as a determinant. Such conceptualization and framework will be more relevant to policy making.

Methods of vulnerability assessment

Vulnerability, being a theoretical concept and multidimensional (Hinkel, 2001), is 'notoriously difficult to measure' (Crane et al., 2017). Considering that the definition of IPCC is the most adopted one in the context of climate change vulnerability, any assessment should ideally capture the future climate, examine its potential impact on agricultural performance (e.g. crop growth and yield) and then see how adaptation action reduces that impact. The resultant impact is considered as vulnerability. Such an operationalization of vulnerability assessment was done through crop simulation modeling (e.g. Olsen et al., 2000; Pathak and Wassmann, 2009; Boomiraj et al, 2010; Srivastava et al., 2010, Abdul Harris et al., 2013) and econometric methods (e.g. Ajay Kumar and Pritee Sharma (2013); Narayanan and Sahu, (2016); Praveen Kumar et al., (2014). Such methods are data and skill intensive and cannot easily be scaled up.

'Indicator method' is the most used method in assessing vulnerability for identifying hot spots of vulnerability to climate change. The method involves identification of indicators of different dimensions of vulnerability and risk, normalization and aggregation. The individual indicators can be combined into component and final indices of risk or vulnerability using weights derived from a variety of methods such as principal component analysis, factor analysis, analytical hierarchical process, expert consultation, etc. The choice of such methods is dependent on the nature of data, skills available, etc. The process of constructing vulnerability indices following indicator method is depicted in the following figure.

Process of building vulnerability and /risk index

Summary and conclusion

The term vulnerability has emerged as an area of multidisciplinary research in different thematic areas such as disaster management, poverty measurement and climate change. The term has been defined and interpreted in many different ways. In the context of climate change, the definitions and frameworks suggested by the IPCC have been often used and many different vulnerability assessments used these frameworks. Vulnerability assessments have over time became more multidisciplinary, more integrating in terms of climatic and non-climatic information, more stakeholder participatory and more policy oriented. Though many approached and methods of vulnerability are evident in the literature, the choice of such approach and method should be more determined by the context and purpose of vulnerability assessment.

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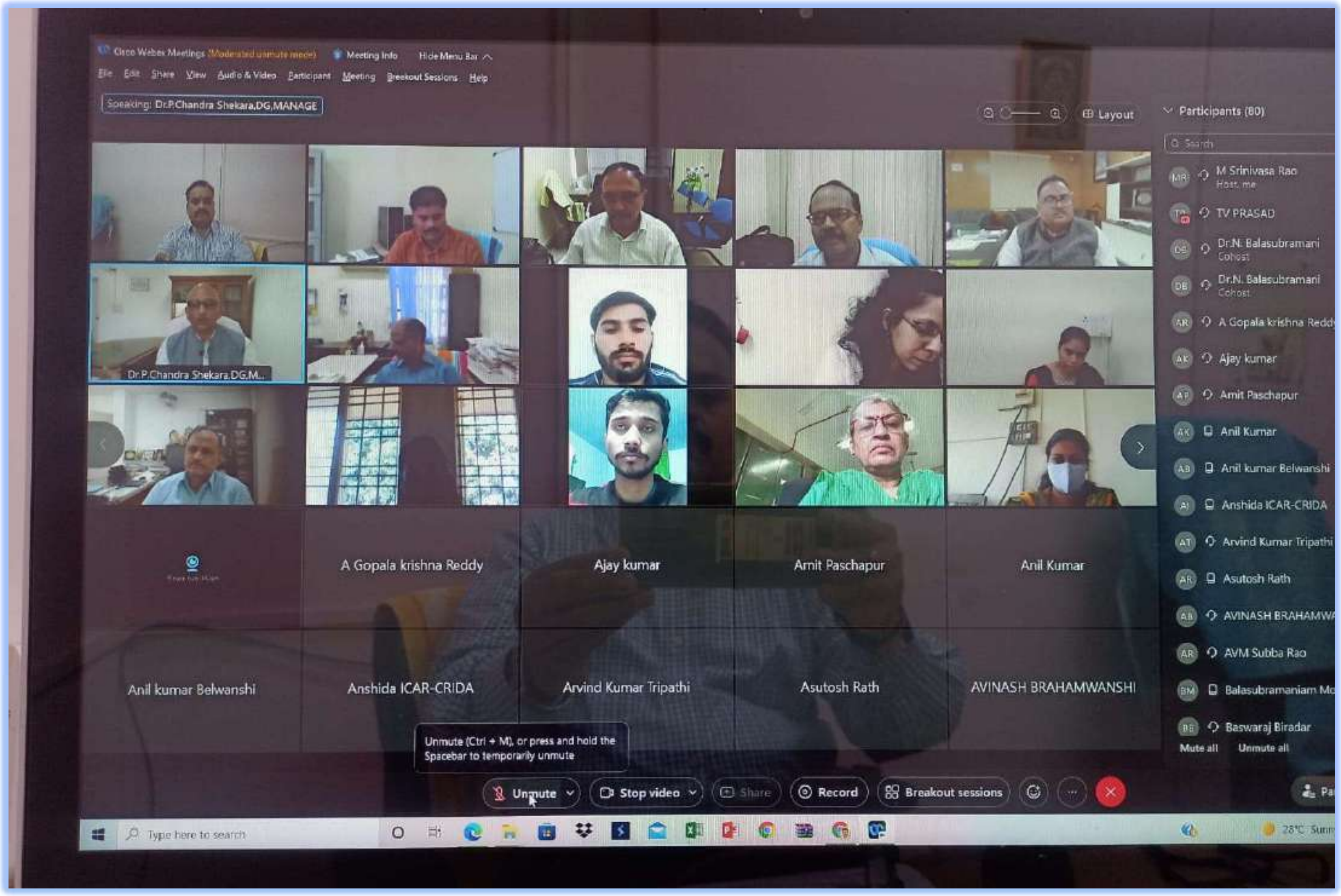

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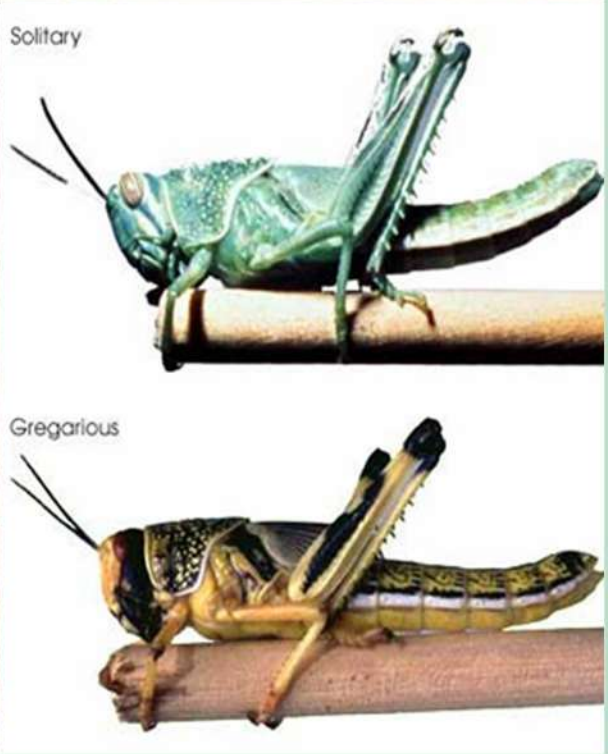

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