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AI and Smart Insect Pest Management: The Future of Digital Entomology

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Artificial intelligence (AI) is game changer in aspects of insect pest management with its ability to quickly identify pests, automate monitoring and help estimate and predict outbreaks. To detect the insect using smart insect traps, IoT sensors, computer vision and drones can give real time pest population and crop condition data. These can be used in conjunction with integrated pest management (IPM) to aid in early detection, specific control measures and minimizing the need for unnecessary pesticide use. These limitations, however, are not without issues such as data availability, variability in the field, species identification, cost, model reliability and ethical considerations. The combination of AI and entomological knowledge thus opens a potential avenue for more accurate, sustainable and intelligent pest control.

Keywords: Artificial Intelligence, IoT Sensors, Integrated Pest Management, Sustainable

Insects are one of the most varied and ecologically important groups of organisms on Earth but only a small number of these species can be serious agricultural pests. They cause crop damage directly through feeding on many part of plant directly and indirectly as a vector of plant pathogens. Farmers and entomologists have depended on field scouting, trapping and personal experience coupled with a microscope to monitor and identify pest populations for generations. These methods are essential parts of integrated pest management (IPM) but in today's agriculture new challenges are emerging – both insect numbers may vary rapidly across large areas and there may be a shortage of trained staff to monitor this process continuously (Rahman & Ravi, 2022). But that is changing with the advent of artificial intelligence (AI), computer vision, Internet of Things (IoT) devices, remote sensing, drones and robotics and advanced data analytics (Kiobia *et al.*, 2023). Technologies are establishing a new discipline that can be called 'digital entomology' in which insects are observed, identified, counted and interpreted with digital technologies. Digital entomology seeks to generate ongoing streams of agricultural biology knowledge instead of relying on ad hoc human observations. It's a paradigm shift in agricultural pest management—from reactive pest control to predictive pest intelligence. AI doesn't need to take the place of the farmer or entomologist. Rather, it can give them more information, faster analysis and earlier warnings, enabling biological knowledge and human judgment to be more effectively applied.

Going from traditional pest monitoring to smart pest management

Normally, insect pest monitoring takes place by making periodic field visits. The agricultural officer, farmer or scouting walks the crop, takes samples of plants, looks for symptoms, picks insects up and counts how many insects are present. Other traps that can be used include sticky traps, pheromone traps and light traps, as well as sweep nets. Collected insects then identified, sometimes with the assistance of taxonomic keys or specialist. This method gives good information but is labour intensive and impractical on thousands of hectares. A key constraint is that populations of pests are not static. The number of insects found may be low one day in the field and many the next day due to the weather, humidity, rainfall or crop conditions. In a sampling system which is only measuring one observation per week, important changes in the field between the samples might not be detected. Smart pest management seeks to overcome this problem by using continual monitoring and automated analysis. Traps can be used to observe insects, sensors can monitor environmental conditions, drones can monitor crop damage and cloud or edge computing can process the data they provide. These observations can then be used to get useful biological information through AI algorithms.

The following is a summary of how the transformation is completed:

S. No.	Traditional approach	Digital approach
1.	Periodic field scouting	Continuous monitoring
2.	Manual insect counting	Automated counting
3.	Expert identification	AI-assisted identification
4.	Separate observations	Integrated data streams
5.	Reactive management	Predictive management
6.	Field-wide decisions	Spatially targeted decisions
7.	Human-only analysis	Human + AI analysis

The goal is not to replace the classical entomology. Rather, digital technology can provide a much greater spatial and temporal scale of observation for entomologists and farmers and can be operated from a few locations instead of a single one.

Artificial Intelligence: Train the Machines to Identify Insects

Automated insect identification is likely the most prominent AI application in entomology. Millions or thousands of insect images can be used to train modern computer-vision systems. During training, the algorithm is trained to form visual patterns of various species or taxonomic groups. The patterns can consist of body shape, colour, wing structure, antennae, legs, surface markings and other morphological characteristics. Deep-learning methods, especially the convolutional neural network (CNN)and the recently emerged transformer-based vision models have shown great promise in insect classification and detection. Deep-learning systems can learn visual representations from labelled images, as opposed to a programmer having to define them manually. But insect identification is not as easy as it sounds! The external form of two species can be almost same, while the same species can differ due to sex, developmental stages, geographic population and environmental factors. Therefore, in addition to the development of better algorithms, high-quality biological data are also essential for the future of AI-based insect identification. Images should depict the diversity found under actual farming conditions. Human-in-the-loop identification is thus one of the key concepts in agricultural AI. The system doesn't have to say that the computer is certain of its identification of the insect but it could give a probability and ask for expert confirmation if it doesn't have much confidence. This would be a system that would integrate the biological expertise of the entomologist with the speed of the AI.

Smart Insect traps: adding eyes and intelligence to a trap

The conventional insect trap is a very simple, yet effective entomological instrument. They can be sticky traps, pheromone traps, light traps or any other sampling method—all intended to capture insects so their numbers can be counted. One problem with this is that someone has to check the trap and count or identify the insects. Smart insect trap tries to do this automatically. Using a camera, it is possible to take photos of insects when they reach the trap or when they are captured by the trap. The image can be sent to an onboard computer or edge-AI device and the number and kind of insects can be determined. The information can then be shared to a central database/mobile application. A network of smart traps could be implemented to continuously track insect populations. Such a system may indicate the time and place of the onset of pest build-up and the differences in populations between fields (Leybourne *et al.*, 2025). The value of the technology is not just automation. It is only with its time resolution that it has real value.

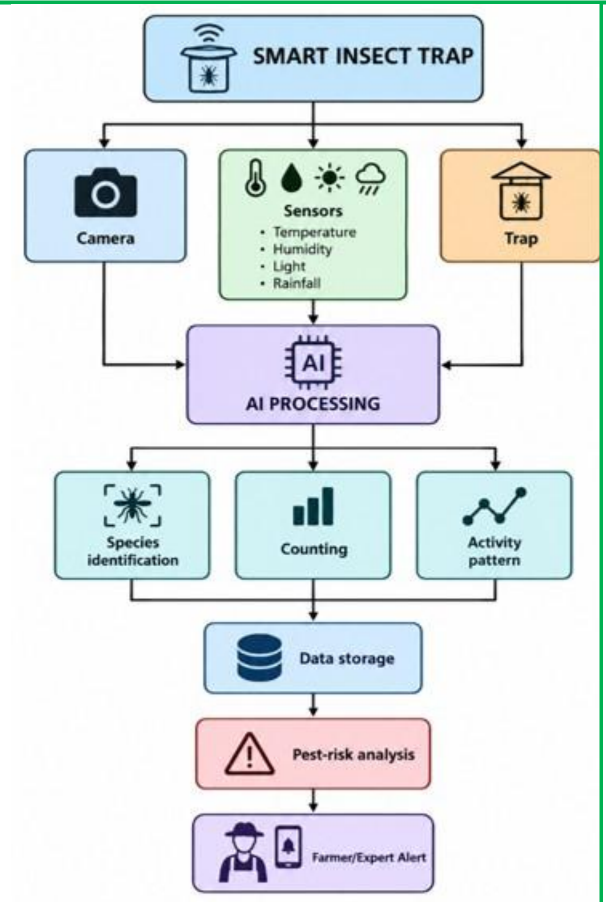


Fig. 1: Concept of an AI-enabled smart insect trap

Insect image
↓
AI detection
↓
Species identification
↓
Automatic counting
↓
GPS/location information
↓
Spatial analysis
↓
Pest-density map
↓
Hotspot identification
↓
Targeted monitoring/intervention

Fig. 2: From insect image to pest-risk map

Beyond Identification: Counting, Mapping and Understanding Pest Populations

Knowing what insect you have is just a first step in pest control. In an IPM context, dynamics of abundance and absence seem to be significant more than just presence or absence. An individual pest and a large pest population are two very different pest management problems. By using computer vision, automated counting can be achieved, where individual insects are identified within a photograph. Object-detection algorithms can detect the presence of insects within an image and segmentation algorithms can separate overlapping insects. Tracking methods also can give information on insect movement and behavior under controlled monitoring conditions (Hartbauer, 2024). If 15% of the field is infested, for instance, with a large population of insects, it may not be worth treating the entire acreage, since there is little amount of insect bait on the balance 85%. Alternatively, the affected area may be subjected to scouting or specific management. This is a significant step towards precision entomology, where decisions for management are made based on the present spatial distribution of insects and not the assumption of uniformity throughout a field.

AI Starts Predicting Pest Outbreaks

Perhaps the most important application of AI is not just identifying what's going on now but forecasting what might happen next but how it integrated with the environmental and give the prediction of pest outbreaks. Environmental factors play a significant role in the development and growth of insect populations. Reproductive, developmental and survival of insects can be affected by temperature, humidity, rainfall, wind, stage of crop development and food availability. Gathering historical information can also provide clues to the seasonal emergence of pests.

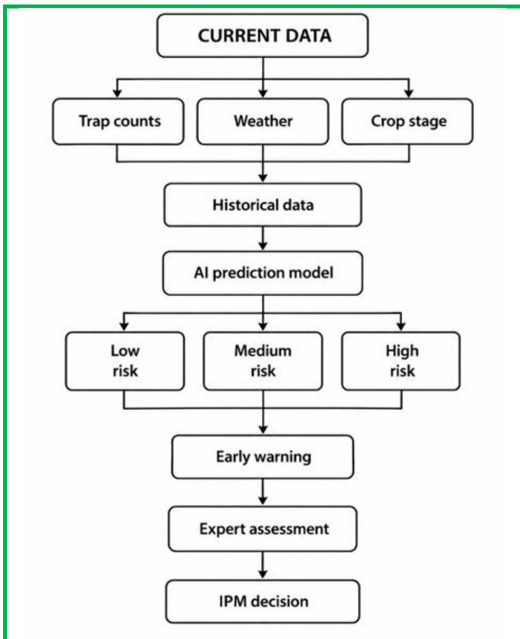


Fig. 3: AI-based pest outbreak prediction

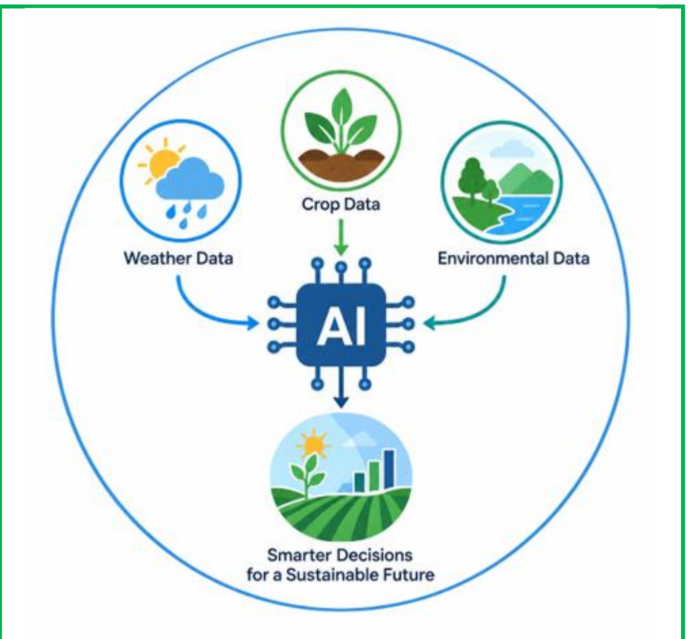


Fig. 4: Integrating AI with Weather, Crop and Environmental Data

Integrating AI with Weather, Crop and Environmental Data

Insects are not independent of their habitat. Insects, crop, weather and surrounding ecosystem are all factors that can contribute to a pest outbreak. Thus, the future digital pest-management system should NOT be based solely on insect photos. Now consider a system taking input from a smart trap, weather station, drone and crop and monitoring camera simultaneously. The traps record the number of insects. The weather station keeps data on favorable temperature for insect development. The crop camera shows that the plants are in a vulnerability growth stage. History tells us that this has happened before and led to an outbreak. Individually, none of these observations may be sufficient. Combined, however, they offer a much more solid grounding for prediction. This is where multimodal AI comes into existence. Multimodal systems can be based on images and other sensor parameters but can also incorporate geographical information, weather conditions, historical information and expert information.

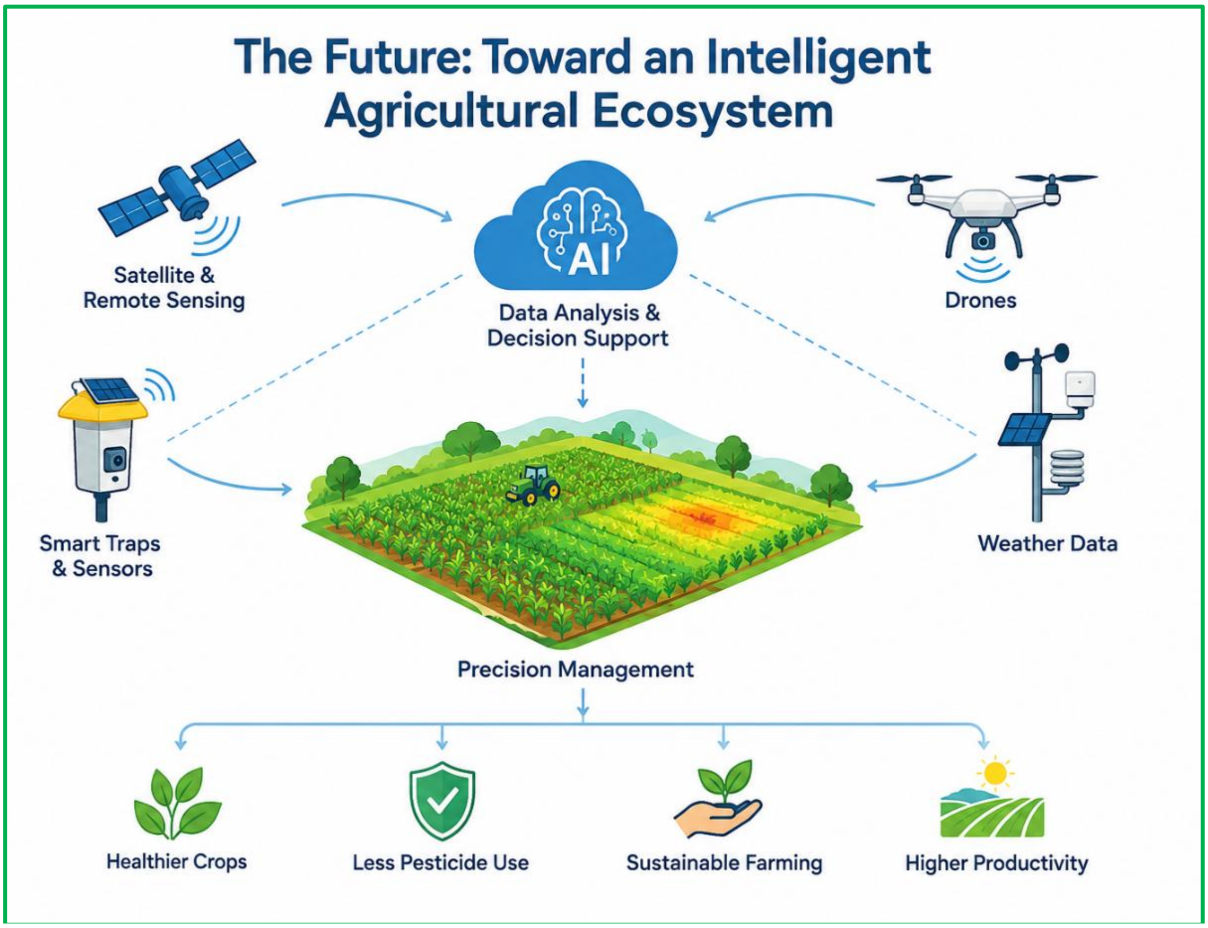
Protecting Beneficial Insects: AI Must See the Whole Ecosystem

One challenge in designing automated pest management systems is designing technology that "only" sees pests. Agricultural ecosystems are full of diversity of organisms like biological control agents, pollination and ecosystem functioning are accomplished by predator beetles, parasitoid wasps, lacewings, bees and butterflies, etc. If an AI system detects only a threat of insects, then it may be a driver for unhelpful management. The future of digital entomology should thus be focused on sorting out pest, natural enemies, pollinators and other organisms.

Suppose that aphid numbers are rising in a field. In a traditional automatic system, a warning could be emitted as soon as it was detected. An ecologically smart system might also be able to identify rising numbers of ladybird beetles and parasitoids. The recommendation for the management may then be to monitor instead of insecticide. To develop an AI pest exterminator is not the ultimate goal but an AI ecological decision-support system.

Smartphones, Drones and Robotics: Bringing Digital Entomology into the Field

Digital entomology won't be limited to stationary monitoring stations. The smartphone, drone and agricultural robots can expand coverage of insects throughout the landscape. If a farmer could take a picture of an unknown insect using a smart phone and send it to a computer that has an AI application, he could get a preliminary answer. Such a system could also contain data on the potential importance of the insect, similar species and if expert confirmation is recommended. Drones offer an alternative viewpoint. Drones can survey a large area for crop stress, feeding damage and spatial patterns related to pest infestations, rather than observing individual insects. Repeatedly surveying with a drone can help you determine the changes in damage over time. Robotics is an additional step. An autonomous agricultural robot could be able to move between crop rows, take pictures and determine pest hotspots and conduct highly localized work. Such systems may integrate machine vision and GPS, mechanical control or precision application technologies.



Challenges, Risks and Ethical Questions

❖ **Challenge**

- **Small and inadequate datasets** – AI needs a vast array of high quality and well-annotated images of insects to successfully identify species.
- **Species level identification** – Many species of insects are morphologically very similar, which makes the identification difficult even for AI.
- **Real agricultural conditions** – AI performance can be affected by lighting, background, weather or insect orientation and image quality.

❖ **Risks**

- **Misclassification** – AI can misidentify a beneficial insect as a pest, or a pest as an innocuous species.

- **Misaligned forecasts** – If predictions are incorrect, this can result in the use of pesticide, or other management action, that is not warranted.

❖ **Ethical Questions**

- **Ownership of data** – It must be determined who owns data of insects, crops and environment taken from farms.
- **Farmer privacy** – Location information, crop production information and information regarding farm management should be privacy protected from unauthorized access.
- **Explainability of AI decisions** – Farmers and scientists should be able to know the reasoning behind the identification or recommendation made by the AI system.

Conclusion

AI can revolutionize the traditional pest management approach from reactive monitoring to predictive and precision pest management. Smart traps, computer vision, sensors and drones coupled with predictive models can enhance the early detection signal and help to make decisions in time. Nevertheless, AI must be used in conjunction with and not instead of, entomologists and farmers. Methods that integrate artificial intelligence with biological knowledge and IPM principles may be utilized to create sustainable pest management solutions that will ensure the protection of crops, beneficial insects and the environment.

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