Leveraging on Agricultural Entomology in Precision Farming for Sustainable Agriculture and Food Security

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ABSTRACT

Leveraging on agricultural entomology in precision farming for sustainable agriculture, food security and other environmental benefits was reviewed. Precision farming (PF) is a new approach to farm management, a strategy in which detailed and location-specific information is employed to precisely manage farm production inputs. The strategy ensures that farm production inputs such as pesticides, herbicides, seed, fertilizer and water are best utilized to achieve sustainability when applied where necessary and as required. PF leads to cost reduction, efficient use of production inputs, increasing size and scope of farming operations without additional labour cost, improvement in site selection and improvement in production process control, improvement in record keeping and product tracking and reduction of potential pollution. The suggested technologies in precision farming include global positioning system, equipment guidance system, mapping software, precision crop input application technologies and yield monitoring systems. These components should be organized into essential building blocks in order to create a functional system. The roles of agricultural entomology in precision farming for sustainable agriculture and food security were discussed. Precision farming, a veritable tool to fight against insect pest, the new frontiers in insect pest management and the application of precision farming in integrated pest management were also discussed. The utilization of low cost technologies for precision farming was advised- to improve effectiveness of farming operations, thereby boosting agricultural production to enhance sustainability and ensure food security.

Keywords: *Entomology, Precision farming, Low cost technologies, Food security, Sustainability.*

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Highlights of this paper

- This is one of the few papers that present classical review on leveraging on agricultural entomology in precision farming for sustainable agriculture, food security and other environmental benefits.
- Unequivocally, the paper highlighted that agricultural entomology contributes substantially to precision farming for increased agricultural sustainability and food security. This is possible with low cost technologies in order to improve the effectiveness of farm operations, the paper concludes.

1. INTRODUCTION

Precision farming is a new approach to farm management and a strategy in which detailed and location specific information are employed to precisely manage farm production inputs [1]. Precision farming is synonymous with precision agriculture, prescription farming and site specific management. McLoud, et al. [2] described precision farming as a management system based on information and technology, site specific and which utilizes data sources such as soils, crops, nutrients, pests, moisture or yield for the optimization (sustainability, profitability and environmental protection) of farm production. Therefore, originally, precision farming is the utilization of every space on the farmland to the best of its capability and also treating it according to its needs. Notably, this could only be achieved if the soil and crop characteristics unique to every part of the field are known.

The justification for this novel strategy is that farm production inputs such as pesticides, herbicides, seed, fertilizer, water would be best utilized (achieving sustainability) when they are applied where necessary and as required. This management approach simply focuses on doing the right thing, at the right place and at the right time. This strategy should be of interest to every farmer at all levels as well as policy makers as it provides a clear means of improving economic and environmental sustainability of agricultural production. In many countries, every part of a field is still treated as a single unit of production despite inherent variability across the field; signaling that decision for each field is primitively based on the average condition of the entire field leading to wastage and pollution. In precision farming, field is segmented into smaller manageable units with specific characteristics which allow for site specific management for maximization of output. Potential impacts of precision farming are many.

These include:

i. Cost reduction.
ii. Efficient use of production inputs.
iii. Increasing size and scope of farming operations with no additional labour cost.
iv. Improvement in site selection.
v. Improvement in production process control, thereby increasing quality and value of produce.
vi. Improvement in record keeping and product tracking (for food security and environmental benefits).
vii. Reduction of potential pollution (due to ineffective or efficient input application).

These benefits may be clear from the technical point of view; however, a farmer in the field might be primarily driven by economic return of this strategy but with the economic return comes the added environmental benefit. Targeted (location-specific) and reduced application of nutrients, pesticides and water can bring about significant soil and water quality benefits. Furthermore, such targeted and controlled application could significantly reduce the number of times equipment travels across the field, thus, reducing erosion and soil compaction [3]. Currently, there are many tools that can help to manage in-field variability and adopt a precision farming management strategy employing the latest advances in ICT (information, communication and technology) and GIS (remote sensing and geographic information systems).

2. METHODOLOGY AND TECHNOLOGY IN PRECISION FARMING

2.1. The Global Positioning System (GPS)

This is the key to precision farming, and allows for the calculation of the position of the receiver on earth from radio signals broadcast by satellites orbiting the planet. A GPS receiver location computation often has errors or inaccuracies (atmospheric interference and deliberately signal degradation for security reasons- selective availability) which are not acceptable in precision farming. Thus, there is a need to adjust the signal received by this receiver to improve its positional accuracy, using a fixed-based station with a precisely known position. This would then be used to correct the satellite-based position data. This adjusted position data are referred to as differentially corrected GPS or DGPS. This can be used to know the position of equipment operating in the field, field sample collection points and collections which include yield data and fertilizer/herbicide/pesticide application data.

2.2. Equipment Guidance System

The GPS can be used to design a guidance system such as auto-steer. Auto-steer controls the steering of agricultural equipment, using a combination of real time kinematic (RTK) correction of GPS signals, software and hardware which allow the input of control maps and mechanical equipment to steer tractors. Another type of guidance system in precision farming is the light bar guidance system Figure 1.

Figure-1. An example of a light bar guidance system.
Source: McLoud, et al. [2].

This is mounted in the cab of the tractor/agricultural equipment and provides direction for the operator to follow via a display of horizontal light. This is less accurate (and less expensive) than auto-steer; it is adequate for spreading or spraying operation.

2.3. Mapping Software

This is the platform on which the positional and attribute data collated is stored, processed and analyzed. The software is available at different levels of capabilities; from low-end packages for map creation, display with limited analysis capabilities to high-end (GIS) software with extensive toolset for data management, processing, analyses and visualization. A host of attribute data could be collected from locations across the field, and dataset collected could include yield and soil attributes (physical, chemical and biological). Thus, data could be raw (actual measurement) collected directly from field/ field scouting. It could also include data from laboratory analyses of samples collected as well as interpolated data using geo-statistical tools within the mapping software. Each of these attributes is stored as layers within the mapping software.

2.4. Precision Crop Input Application Technologies

Variable rate technologies (VRT) are machines capable of changing their application rates in response to their location, thus allowing for precise application of inputs at specific locations. These machines are available for a variety of inputs such as fertilizers, seeds, herbicides, pesticides, irrigation water. VRT is supported by a GPS receiver, a computer controller and a regulated drive mechanism on the applicator- a work for location specific application of inputs based on maps (data and model) previously created with the mapping software. The cost of this system depends on its capability (single input applicator to multiple input applicator). The system works on the basis that the controller adjusts the flow rate of the inputs. The GPS receiver (allows the computer to recognize where the tractor is on the field), serves as the go-between for the applicator and the map input showing the desired application rates Figure 2.

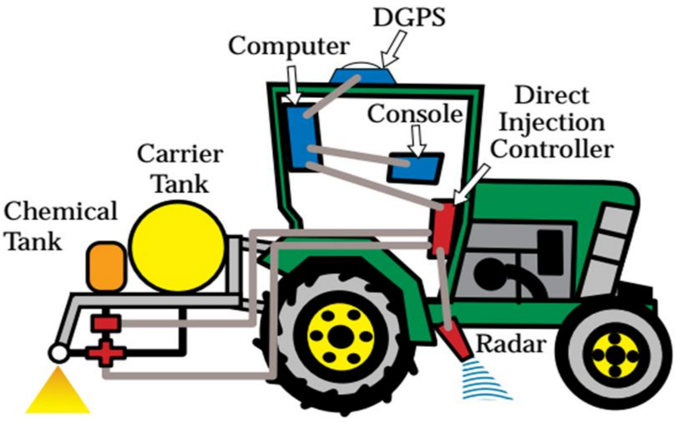

Figure-2. Representation of the components of the variable rate technologies for chemical application.
Source: Searcy [1].

In essence, a map must be prepared at the outsets, based on the knowledge of the field- application plan and with this map the application of input is automatically controlled as the vehicle traverses the field.

2.5. Yield Monitoring Systems

Using mass flow sensor or a scale, yield monitoring system continuously measures the weight of the harvested crop. This captures yield variability across the field, as the system measures and records the amount of crop weight harvested at any point across the field. The harvest must therefore, be equipped with GPS receiver and a yield monitor. The yield data are forwarded to the onboard computer which measures yield tagged with its location of harvest and stored. The data stored are later retrieved and transferred to the mapping software to produce a visualization of the yield data. This system is available for grain, forage and cotton crops [2]. Yield information could serve in the identification of high and low yield areas, informing decision of input adjustment for maximisation of field productivity. Thus, a highly variable field would benefit more from precision farming.

2.6. Field Data Collection/ Mapping with GPS

Data to inform the decision on the input application should be collected fully to get a very clear picture of the soil properties across the field. Grid sampling adopts a fixed pattern for soil sample collection from the field using a grid square. It can be very expensive and time consuming but should form the basis for development of more sophisticated sampling technique [2]. Determination of the size of the grid could be based on the known variability of the field and the value of the crop to be cultivated. As such, higher value crop may require smaller grid size. Directed sampling, targeted or zone sampling could also be applied based on the prior knowledge of the field (that is, observed spatial pattern of soil type, management history, remotely sensed data, soil colour), as such sampling is carried out at locations where soil (or topological) changes are observed. The locations of these sampling points are recorded with GPS and entered into the mapping software to create layers of the field parameters. Since data are collected for a number of points across the field, there is need to use geo-statistical techniques (tools within the mapping software) to interpolate the parameters to cover the entire field.

2.7. The Building Blocks

In putting all these components together to create a functional system, the components need to be organized into essential building blocks for the elucidation of the role agricultural entomology plays in precision farming. These are:

i. Background data: using adequate sampling, remote sensing and existing data, spatial information about the field is developed. These form the background data which need to be geo-referenced (ascribed to a location on the field) using GPS.

ii. Record-keeping system: This is very important for the success of precision farming deployment and implementation. Data collected across extensive areas of farmland can become overwhelming when not properly organized and stored. As such, GIS software and other commercial software specifically designed for precision farming allow farmers to organize, store and process data collected. Well-organized records become the background data on which decisions are based.

iii. Analysis and decision-making process: This involves the development of the input application plan, based on the record-keeping system and the background data. Data collected need to be analyzed to create meaning and understanding that could inform decision making. Results from analyses of the data aid in solving the problem of how much input should be applied where to maximize return on investments (time, money and efforts). Farmers may wish to consult experts in this respect, as they have the capacity to deal with the complexity and provide adequate results in time (ensure timely execution of farming operations).

iv. Specialized implementation equipment: These are the essential machineries which ensure precision farming operations. These include the GPS receiver, GPS guidance systems, VRT and yield monitors. Other equipment such as soil parameter meters (pH, moisture, temperature, conductivity) may also be required for data collections.

v. Evaluation and revision: After the execution of the plans over a cropping season, there is need to evaluate the results obtained in the field (yield-output). This would help in assessing the efficiency of the plans and operations, thus inform revision or otherwise of plans for the next cropping season, essentially supporting refinement of plans.

3. AGRICULTURAL ENTOMOLOGY AND PRECISION FARMING (PF)

3.1. The Roles of Agricultural Entomology in PF for Sustainable Agriculture and Food Security

Okiwelu and Noutcha [4] reported that agriculture covers about one-third of the surface of the earth and the largest user of biodiversity and its components. Man livelihoods are dependent on several factors but majorly are shelter, food and clothing. The world population is increasing at alarming rate of 2.2% and at this rate therefore; the current world's population of 6 -7 billion will hit 11.5 billion by 2100 with over 87% living in developing countries in Africa, Asia and Latin America [5, 6]. By 2020 such population growth might lead to higher food demand. Lale

[6] estimated 75% of the world's poor live in rural areas in developing nations in Africa and Asia and proposed that management and preservation of natural environment, ecological systems, and biodiversity are essential for sustainable development. To achieve this, Oben-Ofori and Boateng [5] suggested the following steps:

i. Doubling food production globally in the next 20 years.

ii. Trade and reduction of urban poverty should make food accessible to the entire urban population.

iii. Farmers especially on degraded lands should acquire new means of generating income.

Across many developing countries, where issues of food security and poverty are major issues, managing insect pests could be one of the keys to sustainable food security [7]. There is a clear understanding that food security cannot be achieved merely by expanding cultivated areas (to meet extra demand), but rather increase in productivity at all levels (reducing wastage due to insect pest on farm, store, on transit and during processing) should be advocated. Reduced food production has led to reduced caloric intake and increased malnutrition estimated at 300 million people globally Zakka [8]. Ayertey [9] estimated that if a conservative loss figure of 10% due to storage insects was applied to major cereal crops produced worldwide, the total food loss to mankind was enough to sustain the whole of Africa's population of nearly 470 million people for 16 months. Recently, FAO estimated that 23% of all food produced in the world was lost to insect pests which are rightfully called stealthy thieves or kleptomaniacs [10, 11]. When converted into calories such losses amounted to 20% loss of food produced. Lipniski, et al. [12] reported that one out of four food calories intended for mans consumption is lost due to insect pest infestation either quantitatively or qualitatively. This figure is alarming and an indicator that food security is under threat.

The practice of agriculture especially with the use of modern technology such as inorganic fertilizer, pesticides, tractors and other machinery came with enormous cost such as destruction of ecosystem, loss in biodiversity, soil erosion and ecological pollution [4]. This has led to search for alternative agriculture and/or precision farming with emphasis on agriculture practice that increase sustainability and food security. FAO [13] defined sustainable agriculture as an integrated system of plant and animal production practices having a site specific application that would cover the long term:

i. Satisfying human needs for food and fibre.
ii. Enhancing environmental quality and natural resource base upon which the agricultural economy depends.
iii. Utilizing all the most efficient use of nonrenewable resources, and integrate where appropriate natural biological cycles and controls.
iv. Sustain the economic viability of farmer operations.
v. Enhance the quality of life for farmers and society as a whole.

Another essential step towards sustainable environmental development is the economically efficient management of natural resources in a proactive approach rather than reactive as often seen. Globally, the proactive approach is fast becoming a trend which permits continued improvement in the present quality of life at a lower intensity of resources [14].

3.2. Traditional Approach to Insect Pest Management

For centuries, farmers had been planting and harvesting their produce according to their ancient traditional knowledge such as early harvest technology to escape insect invasion from farm to store, but such technologies are fast becoming unreliable due to several factors such as climate change and advances in technology. Rural farmers who make up the bulk of farming communities will need to compliment their local knowledge with modern technology that advocates precision farming, through pest forecasting and prediction, for better management strategy to promote crop performance and eco-friendly control measures.

The use of pesticides in agriculture and horticulture is almost as old as farming, but increased steeply after the advent of DDT (dichlorodiphenyltrichloroethane). This singular act has continued to raise major public concerns about the use of pesticides that leads to bioaccumulation and biomagnifications within the food chain and the hazards posed by industrial waste and pollution on the stability, distribution and outbreak of pest populations. These changes can also have an adverse effect on the natural enemy efficiency. It is known that application of an insecticide may create patches containing a few surviving hosts which may not be detected by the natural enemies. This might force them to leave the field in search of alternative hosts, though stable equilibrium of predator-prey populations is not sacrosanct for satisfactory biological control. The traditional method of mixed cropping (heterogeneous cropping) that played an important role in pest management by ensuring that spatial arrangement of crops influences the ecology of pest species is becoming obsolete. It is gradually being replaced by the system of monoculture due to the establishment of large scale farming with particular interest in a single crop. This has led to the over reliance and indiscriminate use of insecticide to combat insect pests in order to maximize output. The use of uniform application of pesticide across the field and on an area-wide basis drastically simplifies arthropod communities and impoverishes them of natural enemies thereby reducing their cluster distribution [15] and minimizing the exposure of insect predators and parasitoids to insecticide through site specific or hot spot application [16] as advocated in precision farming which will favour biological control and subsequently reduce pest population and its attendant damage. Precision agriculture therefore seeks to reverse the trend and allow the fine tuning of the quantity of inputs, its time of application and the exact spot of application in the field. Brenner, et al. [17] advocated that pesticide application should only be at hot spot where insect pests have reached their threshold and by so doing it would create a mosaic of communities that differ in species composition and inter-specific interactions and more likely to retard pest population outbreaks. It is believed that this approach would greatly reduce development of resistance in pest population, creating spatial refuges of susceptible pests unexposed to the toxins and conserve natural enemies that slow down the rate of selection of resistance pest population and the release toxic chemicals usually generated from the injudicious use of insecticide into the environment and food chain.

Large scale pesticide industry really dates back to the end of World War II, with the commercial introduction of phenoxyacetic acid, a selective herbicide and the synthetic, persistent, broad-spectrum, organochlorines. Agro chemicals can be a source of huge boom to a farmer especially when used correctly but can also be a major root cause of value destruction; therefore, there must be a balance in the judicious use of agrochemicals possibly only those that are easily degradable, and narrow spectrum and low mammalian toxicity. If usage has to be limited to a very large extent there must be a stringent regulation in this sector from production to its final usage in subsistence and commercial farming in arable crops, permanent crops, hydroponics, horticulture, arboriculture, home gardening and forestry.

3.3. Precision Farming a Veritable Tool to Fight against Insect Pest

In precision farming, the use of agrochemicals in the right combination, at the right time, in the right way should be emphasized. This could be achieved through specific site (hot spot) application and complimented by integrated pest management (IPM). Retreating from complete usage of insecticide would certainly reduce the amount of food produced or stored. Earlier researchers have showed that pests consumed between 35-55% of crops produced and in some cases up to 100% when left unprotected. It is therefore worthy of note that the use of pesticides is still the key to a sustainable agriculture, although its abuse is condemned by the current organic farmers and environmentalist. Elimination of insecticides might lead to colossal global hunger and starvation [8, 18]. The world population is growing at an alarming rate and increase in food supply is becoming an urgent priority Oben-Ofori and Boateng [5]. Oben-Ofori and Boateng [5]believes that globally, food supply is currently sufficient to meet the food needs of the world's population, but surprisingly in the face of such abundance there are still food insecurity challenges. However, humans cannot afford to lose any kilo of food to biological agents of deterioration. Adedire [19] reported that a few insect species comprising about 1% of all described species are man's greatest competitors in terms of food and other possessions and that insect pest depredation is probably the most known agent responsible for global food shortage and their activities have been recorded in tree crops, arable crops and horticultural crops from nursery to storage and from field to post-harvest periods.

There is therefore an urgent need for a paradigm shift to a sustainable pest management plan which is directed at achieving a precise technique to determine when and where the probability of encountering the pest is high and also where it is not located so as to minimize collateral effects of toxics from unnecessary chemical application and creating ways for spatially-based 'precision targeting'. In precision farming, the use of chemicals is site-specific and in the correct dosage as at when due. This approach ensures water quality and higher numbers of natural enemies, for instance. Therefore, in precision farming, field scouting especially for decision making, pest forecasting and correct identification of the pests should be an integral part of the technique. It has been established that the main driving force for precision farming is its economic return to the farmer and environmental friendliness. To achieve this, McLoud, et al. [2] proposed the following steps:

i. Identify the resources concerned for which precision agriculture is to employed and determine the technique that has most positive effect while addressing the problem that is also farmer- friendly.
ii. Generate a background data that is needed o address the problem. In gathering the data, farmer's flexibility and technical ability of data collection should be considered and whether specialized equipment is needed and any value the data may in the overall add to the exercise.
iii. Farmer's technical ability to collecting and keeping geospatial data. This can be done either by hiring a professional or developing the skill in recordkeeping.
iv. Develop a plan on how precision agriculture will be used to address the resources or problem at hand. To achieve this, a consultant may be hired to develop a farm-specific plan to address the problem using precision farming.
v. Determine the type and availability of the specialized equipment required for execution such as light bar guidance system or auto-steer tractor.
vi. Assess and evaluate the plan after each cropping season. The result should be fed back to steps 3 and 4 to allow the fine to fine tune the precision farming system in solving the problem.

Precision farming advocates specific management where environmental impact is minimized by ensuring quality health of water and soil and by extension agricultural sustainability as a result of reduced or targeted application of agrochemicals [3]. The decision for specific management is designated low risk and the use of advanced technologies in support of precision agriculture should include GPS for mapping insect pest infestation based on scouting reports and other data generated *in situ*. Mapping infestation over time helps in predicting insect pest populations. Some scouting activities such as grid sampling for pests will complement advanced technologies for insecticide application. GPS, in combination with additional technologies to reduce the amount of insecticide applied (reduced spray overlap technology and green seeker technology) are required in precision farming. The ability of farmers to understand the current pest pressure will enable them make accurate prediction of future migration pattern, dispersal and other resurgence. This can be achieved through a simple technology such as daily monitoring of insect traps, observation of detailed weather pattern, and other insect forecast tools that could be obtained from local agricultural extension entomologist in our various research institutions. This process must begin with agricultural entomologist monitoring and understanding biology of the pest in question such as migration pattern, larvae hatching time and period, hibernation or aestivation period and factors responsible for it. Others include insect populations and migration patterns for different crops across the regions for short-term and long-term monitoring. When such data with other data on weather trends, physical and chemical characteristics of soil and other specific geographical information are generated then a template or guide showing hot spot locations and pest dynamics at each locality or farm will enable a farmer that is armed with such knowledge to know when and where to apply chemicals or in conjunction with other suitable control measures in an integrated approach.

Adedire [19] expressed that IPM idea was first conceived by Hoskins, et al. [20] as integration of both chemical and biological control methods which are compatible and complimentary. He further emphasized that IPM advocates harmonious use of multiple pest management options to control a single pest or number of pests. He emphasized that irrespective of the nomenclature of the pest management, scientists and environmentalists tend to agree on reduced use of synthetic insecticides and increased emphasis on the use of bio-pesticides so as to minimize adverse effects on non-target or beneficial organism, human and the environment. IPM therefore has been advocated by several workers because of its presumed efficacy, cost effectiveness and reduced adverse effects on man and the environment. Moshe [21] identified few compatible principles of IPM with precision agriculture and they are as follows.

i. Corrective measures should be based on economic and ecological criteria, that is, the use of action threshold.
ii. Maximization of sustainable by the use of resistant varieties, biological and cultural control measure.
iii. Minimization of farm inputs such as pesticide application in classical precision agriculture.

While IPM seeks to integrate the most compatible and complimentary methods of tackling the menace of insect pest in order to maximize output and protect the environment and humans from excess toxins from agro-chemicals, precision agriculture acts to minimize economic and environmental damage through the options of farm inputs such as fertilizer and insecticides. Yet IPM lacks the special components so central to precision agriculture. Fleischer, et al. [22] are of the view that while IPM decisions are based on routine monitoring of pest, precision agriculture collects reliable data on pest density across the field that would allow the creation of management maps using mostly software thereby showing areas of interest such as pest density for spot treatment but VR applicators is probably the challenging step towards the use of precision agriculture.

Effective pest management is based on certain decisions and factors which include economic injury level (EIL) and economic threshold (ET) concepts. Ashamo [23] emphasized the importance of rightful economic decisions in pest management, since one major objective of pest control is to prevent crop damage and reduce loss in order to maximize profit. Therefore, it is important to know the insect population level before engaging in any control measure. This will inform the economic decision which defines the amount or injury which will justify the cost of artificial measure or if the pest is perceived to be a problem [24, 25]. Negating this principle will amount to spending money and other resources which could have been avoided. Ashamo [23] defined EIL as the lowest number of insects/lowest population density that would course economic damage, or the amount of pest injury which will justify the cost of control. Since precision farming attempts to deal with the specifics at EIL, the cost required to control the pest is equal to the amount of damage the pest inflicts. Below it there are no economic losses and above it, economic losses have occurred. EIL concept has been expanded to include concerns about environmental, social and resources management and sustainability [25]. Economic threshold is the number of insects (density or intensity) that should trigger management action. In pest management, the full knowledge of this action threshold is an inevitable tool. The concept sets a limit for timely artificial intervention at a particular pest density so as to prevent the pest population form rising to economically damaging level [24].

Determining the economic injury level and threshold will ensure the use of chemical on the real pest problem rather than on the perceived pest. In doing so, information-gathering by forecasting will give accurate information on pest status, or provide certain information on specific pest problem, its infestation peak, alternative host, or when pest is alien and invasive as a management technique so as to enable farmers know when to scout or begin intervention and also do a site specific or spot application of insecticide thereby maximizing chemical input, reducing cost of purchase and application rate yet ensuring quick and efficient intervention. Pest management concept is a comprehensive pest technology that combines all the available and compatible control measures in order to reduce the status of pests to tolerable levels while maintaining the quality of the environment and ensures farmers maximum yield and profit [23]. This will also ensure judicious use of chemicals, prevention of over remediation and advocating an integration of multiple control approach to achieve long-term pest management tactics.

3.4. New Frontiers in Insect Pest Management

Pest management tactics in agriculture (both field crops and storage system, medical and veterinary entomology) evolved over the years which could be attributed to several factors among which are anthropogenic activities, modernization in farming and style of living, global warming and related activities, availability of sophisticated science and technology such as faster means of transportation and other delivery services. This has led to insect pests developing resistance to chemicals and emergence of invasive alien species. Okiwelu and Noutcha [26] listed some of the new frontiers in pest management: the use of molecular techniques, insect conservation, bio-rational approach to the management of stored product insects, quarantine entomology, forensic entomology, insect genomics and transgenesis, push-pull and semio-chemical-based strategies in IPM, sytematics, macroecology and cultural entomology. Briefs on these approaches from Okiwelu and Noutcha [26] are provided as follows.

i. Molecular biological technique such as polymerase chain reaction (PCR) used in the identification of sibling species of insects complexes [27].

ii. The multiplex PCR or Enzyme-Linked Immunosorbent Assay (ELISA) that could be used in sero-epidemiological studies in detecting parasite antigens or in determining infection rates in vector and their feeding preferences [28, 29].

iii. Near infrared spectroscopy (NIRS) is a recent species identification tool and also recent is.

iv. Bio-rational approach to managing stored product insects. The loss attributed to stored products can be as high as 20% especially in developing nations [26]. The attendant problem with the conventional insecticide usage in the store led to search for alternative approaches. Philips and Throne [30] and Okiwelu and Noutcha [26] stated such alternatives include: manipulating the physical environment, sanitation and exclusion, humidity and temperature control, irradiation, controlled and modified atmosphere, desiccation, impact and removal.

v. Biologically-based controls include the use of pheromones, semio-chemicals, natural enemies, microbial insecticides, insect growth regulators and resistant crops.

vi. Insect genomics and transgenesis. This is a dynamic field that combines traditional paths of inquiry with new approaches using advanced technological development. Recent focus is on gene sequencing by ordering and organizing the gene into libraries [31]. It then becomes a major key to gene discovery, identification of novel targets for new insecticides with regards to application of functional genomics [26]. They also highlighted the possibility of manipulating the genomics concept for autocidal control or in the replacement of a pestiferous strain with a benign genotype.

vii. Push-pull and Semio-chemical-based strategies in IPM. These techniques involve manipulating the behavior of insect pests and their natural enemies through integration of stimuli that make the protected resources unattractive or unsuitable to the pest (push) while luring them towards an attractive source (pull) from where the pest is removed. This technique is non-toxic and can easily be integrated with suitable but compatible methods for population reduction especially in biological control [26].

viii. Macroecology. Okiwelu and Noutcha [26] stated that this approach concept focuses on ecology at geographical scale. Collaboration on ecological studies of pest and natural enemies over their distributional ranges across states is the goal.

ix. Microbial control. This is the use of pathogens or disease causing organisms to reduce the population of insects below the level that they can cause damage [32]. Such agents include bacteria and fungi and application is similar to those of synthetic insecticides but requires an appropriate strategy in order to maximize effective control of insect pests and insect vectors. These include introduction and establishment to achieve permanent suppression of target pests, seasonal and environmental colonization to control pests for more than one generation [19].

x. Entomophagy. Insects play a significant role in human nutrition in many parts of the world including Africa [19]. Insects as protein source are now becoming a major alternative to animal protein that is linked with many environmental and sustainability challenges especially in Africa. These challenges range from limited grazing areas, insufficient feeds and poor veterinary service. Van, et al. [33] reported over 1900 species in 370 genera of edible insects across several orders that are consumed in different forms across cultures Gullan and Cranston [34]. TransEnergy [35] reported an automate process of breeding and raising crickets for food- a system where robotic module is employed to deposit the ideal amount of food and also monitor when the insects need more food to achieve cost effectiveness. In many developing countries, edible insects are harvested from the wild and currently there is no documentation on entomofaunal farming.

3.5. Feasibility on the Use of Precision Agriculture in Integrated Pest Management

Brenner, et al. [17] are of the view that entomologists have a major role to play in ensuring food security through fighting the menace of insect pest infestations and their associated pathogens from destroying the cultivated food in the field and store. Unfortunately, the pesticides being used in combating the menace of most of these arthropods often place us in a precarious position, especially from the environmentalist perspective. At the advent of agriculture pre-dating modernization or technology-driven farming, insects competing with crops or animals were merely hand-picked, which was an aspect of precision farming. As knowledge of science and technology increased, the use of chemicals, especially on a large scale became common, but with the organic agriculture campaign, application of insecticides only when necessary and at a precise spot (site-specific) has been advocated as complementary to precision agriculture. However, the practice is still limited to small farming communities, the move or its adoption among large scale pest control operations is still daunting, impractical to intensively monitor pest populations across large commercial farms.

Moshe [21] acknowledged that the application of precision agriculture to pest management has been a slow process, which they attributed to technological constraints stemming from the dynamic and cryptic nature of disease agents and insect pests. Despite this presumably strong opposition to its adaptation, precision agriculture seems to be the best management option in clustered distribution of such crop pest in farm lands when compared to the adverse effects of pesticides on the human health and environment. Since the use of remote sensing in creating pest management maps is one of the surest ways of predicting pest invasion sites for site specific or hot spot treatments, through monitoring either the plant health status or visible insect by-products such as exuvia,frass and their feeding spots. SPORE [36] further identified hot spot agronomic data essential in precision farming to include plant biomass, chlorophyll rate, leaf area index, emergence rate, water stress, missing plants, height or flowering and differences in vegetation index. When such hot spots are located, the use of biological control agents in combination with selective insecticides with low mammalian toxicity could then be applied as IPM at the detected sites. A major setback in the use of visible sign of infestation could mean that infestation or damage has occurred already and will no longer be a proactive measure but reactive. This therefore suggest that remote sensing based-approach in precision agriculture might be well suited in a relatively stable system such as forest and orchards that are relatively tolerant to pest infestation or delay in its management can be tolerated rather than in arable crop farming that is short lived and highly vulnerable to insect pest infestation. Other technical challenges to the deployment of this technology include the misinterpretation of mere shadow or black area or infrared aerial photographs for presence of infestation foci as was used to monitor brown soft scale populations in citrus [37].

With remote sensing, insect pests can be monitored consistently over years and a multi-year management map can then be generated and such data are transferred to GIS and used to apply pre-emptive measures. Liebhold, et al. [38] reported a map of Gypsy moth showing the existence of consistent distribution pattern of defoliated trees and with such information any area with a history of consistent defoliation over years, control measures are applied to such susceptible areas. On the other hand, since precision agriculture is not targeted at forest trees only, an alternative is to generate management maps for other variables that correlate with pest density such as field topography, soil type and nitrogen and crop yield which have the propensity to induce or reduce insect pest infestations depending on the level. Coll, et al. [39] observed that *Phthorimaeaoperculata* infestation is three times more intensive in clay soil than sandy soils. The infestation rate is directly related to the soil type. They also reported that with GIS, yield across the field for instance when insect presence does not correlate with other factors other than yield, in such case where there is a persistent re-invasion of pest to annul crop showing migration pattern of field infestation at the margins than at the centre over years may suggest the use of hot spot pre-emptive management to the vulnerable part of the field.

4. PRECISION FARMING FOR SUSTAINABLE AGRICULTURE

SPORE [36] in appreciating the role of precision agriculture in modern farming such as better returns on investment and improved livelihoods for farmers around the world expressed fear over its quick spread and adoption in developing countries, where they consider smart farming technologies, including data collection from satellites and drones as still a major setback. However, given the technologies and methods highlighted earlier, one might have the impression that precision farming is impracticable in low and middle income countries due to their peculiar problems and challenges. However, precision farming is even of more important across many of these countries due to increasing challenges of low productivity, high cost of input and attendant problem of pollution (soil and water), land degradation (erosion and loss of fertility and biodiversity) and high insect pest infestation.

This brings up the question, how can precision farming help in the low economy of developing nations? In this respect, we will present a number of scenarios which could utilize low cost technologies already available and can be adapted for use in precision farming in concerned nations, thereby boosting production and improving efficiency and effectiveness of farming operations.

i. With increasing penetration of mobile phones in developing countries such as Nigeria, there is an opportunity to map farmland of many farming communities, thus reducing the need for expensive technologies. Such maps could form the basis for the creation of other background data and records of the farmland, which could be overlaid on extension services advisory maps created from remotely sensed data. These high resolution advisory maps could include application plans for various inputs based on farmer's location, crops, prevalent pest and disease. Using the approach of crowd sourcing or volunteer GIS (VGIS), data across vast area of farm land could be collated, using mobile phones. A simple mobile application developed for farmers in rural communities could collect information on pest (by taking pictures and geo-tagging them and uploading to a central database), keep records of data of activities via picture taking as well and so many other activities. The collection of such could form the basis for visits and advisory services by extension officers.

ii. Growth in the development of cheap, portable, wireless, low power (and solar supported) sensors could also help farmers collect data on their farm which could be sent via mobile phone (including location of the measurement) to an extension services which can quickly automate the production of input application plan for the farmers, based on the data and other ancillary data derived from various sources (remotely sensed, unmanned aerial vehicle- UAV). Geo-tagged pictures from farms on weed, pest and so on, could also be sent via mobile phone to appropriate organization which could quickly do a turnaround on the data provided to advice on application rates and plans. The bottom-line, is that the technology is not a real challenge as there are always opportunity to adapt technology to suite different situation.

iii. Mapping of farmland and partition into grids can now be done by farmers using only a mobile phone. Farmers can walk or ride around the boundary of their farm thus digitizing the extent of their farmland. The boundary now forms the basis for dividing the farmland into grids which would be used for sampling of soil and yield. With these grids in place, farmers can be advised on how to sample their farmland to ensure that the heterogeneity of the farmland is captured. From this, farmers now have visual aids to guide them on where to sample and how to store the data. From this data, geo-statistical analyses can be done to create a yield map or fertility map for the farmer, thus creating a decision making framework for input application and optimization. Technology is no barrier in application of precision farming in developing countries and the benefits are bound to be numerous. However in order to harness this, there is a need to tap into the creative imagination and innovations of farmers, extension officers particularly extension entomologists and researchers (especially, agricultural entomologists). Essentially, we have to begin to see precision farming not as something only the farmers in industrialized countries can do but something all farmers should do irrespective of the status of their economy. Africa currently leads the world in mobile money based on significant barriers faced by the populace. The same can be repeated in terms of precision farming, using our challenges to reinvent, innovate and adapt precision farming to our own peculiar situation. With advocated precision, adaptation and innovation coupled with the exploration of new frontiers in agricultural entomology, sustainable agriculture is obtainable.

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