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Review

Climate-Smart Pest Management in Sustainable Agriculture: Promises and Challenges

Meriam Bouri *, Kadir Sinan Arslan and Fikrettin Şahin

Department of Genetics and Bioengineering, Faculty of Engineering, Yeditepe University, İstanbul 34755, Turkey
* Correspondence: mariem_bouri@hotmail.fr

Abstract: Sustainable development in global and regional contexts has become mandatory to prevent the potential adverse effects of human activities on the environment. While agricultural activities stand as the leading source of degradation and pollution in ecosystems, climate changes are among the most important challenges facing agricultural productivity. Climate-smart agriculture involves farming methods and strategies adopted for the early diagnosis and management of climate crisis drawbacks. Changing climatic conditions affect plant health either through abiotic or biotic factors that influence diverse disease scenarios on a wide range of crops. Therefore, disease management under the concerns of climate change is considered the cornerstone of sustainable agriculture. The climate-smart pest management (CSPM) concept and its role in supporting sustainable agricultural development, particularly the effect of weather changes on phytosanitary issues, are reviewed in this article. Problems in implementation and difficulties in decision-making are among the main challenges facing CSPM, which still has both technological and coordination shortcomings to overcome. Intensifying collaborative activities in scientific and technological research, risk assessment, and surveillance may enhance the current efficiency of CSPM in terms of preserving the sustainable development of agricultural systems. More efforts for capacity building are also needed in developing countries to promote the implementation and adoption of CSPM.

Keywords: environment; disease scenarios; food security; global warming; implementation and decision-making; risk assessment; sustainable development

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1. Introduction

Climate change refers to the ongoing shifts in temperatures and weather patterns, as defined by the United Nations (UN). Although these shifts may be induced by natural events such as variations in the solar cycle, human activities still constitute the predominant cause of climate change, primarily through their contribution to gas emissions such as carbon dioxide and methane [1]. According to the last report of IPCC, emissions of greenhouse gases (GHG) have already increased the global temperatures by nearly 1.1 °C compared to the period of 1850–1900, which is used as an approximation for the preindustrial temperatures. This increase in overall temperature is expected to reach 1.5 °C within the next few decades and will affect all regions of the Earth [2].

Many environmental changes due to global warming are taking place on our planet, such as intense heat waves, rising sea levels, shrinking glaciers and ice sheets, droughts, wildfires, extreme rainfall, shifts in freshwater and marine species, etc. [1]. Reported negative impacts of climate change on crop yield have also increased. For example, soybean and maize are the crops that are most severely affected by climate change with yield reductions of −16.7% and −10.8%, respectively [3]. Therefore, global food security may be threatened by climate changes in terms of quality and quantity.

The phytosanitary issues caused by climate changes are resulting in important yield losses and, therefore, are cited among the biggest challenges faced by the global food security and sustainability of agricultural systems [4]. Climate change is also affecting pest population dynamics and distribution directly and indirectly [5] through its role in the emergence of invasive species and new diseases [6]. Above all, phytosanitary problems are becoming increasingly unpredictable [7] owing to the global shifts in temperature, precipitation patterns, GHG levels, and extreme weather events [8].

By 2050, global food production will need to increase by 70% to satisfy the growing needs and changing diets of the world population [9]. According to Savary et al. [10], pests account for 20% to 40% of losses in the world's food supply. Although the growing development in agricultural techniques to boost production in the last decades succeeded in increasing both crop yields and incomes, modern farming systems relying on new technologies, mechanization, and excessive chemical uses lead to serious issues of different dimensions. For example, soil degradation, pollution (in terms of air, soil, and ground and surface water) in ecosystems, threats to human health, and depletion of biodiversity are among the main environmental problems imposed by modern farming practices [11]. From the socioeconomical perspective, these farming systems promoted the disintegration of rural communities, deterioration of working conditions and safety in the workplace, and concerns about market power and competition in the agri-food industries [9].

As climatic change intensifies and/or creates new pest threats, the global agricultural system needs to adopt novel farm and landscape management practices that address these threats. Actions should not be limited to the farming level only, but rather be extended to multiple levels, including geographical scales, environmental economics, and social sustainability, as well as national and international food security [12]. Sustainability in agriculture refers to the resilience and persistence of agricultural systems to buffer stresses and prevail over long periods without harming or depleting the resources for meeting the needs of the current and future generations. Conservation of resources is critical for agricultural productivity. Sustainable agricultural systems support soil health, minimize water use, and promote lower pollution levels of groundwater, air, and GHG emissions [13].

Climate-smart agriculture (CSA) is the term introduced by the Food and Agriculture Organization of the United Nations (FAO) to describe a novel approach in farming with the ultimate goal of ensuring food security via establishing actions, guiding entire agricultural systems for sustainable development, resilient activities, and adaptable strategies under climate changes [14]. An important component of the CSA approach is the climate-smart pest management (CSPM) panel which provides many advantages in sustaining agricultural systems by minimizing chemical uses. However, CSPM still has some limitations; therefore, this review focuses on the concept of CSPM and phytosanitary issues related to climate change to elucidate the areas in need of more efficient interventions. It also explores the potential of adapting pest management to weather events to support the sustainable development of agricultural systems. Challenges and perspectives in the adoption and implementation of CSPM will be discussed as well.

2. Conceptual Overview

2.1. Climate Smart Agriculture (CSA)

The concept of CSA was first introduced in 2009 when discussions were initiated on approaches for the development of more sustainable agricultural systems by focusing on linkages between combating climate change and achieving food security [14]. The CSA concept was first introduced officially in 2010 by the FAO in a paper entitled "Climate-Smart Agriculture, Policies, Practices and Financing for Food Security, Adaptation and Mitigation" [15]. Since then, the CSA concept has been elaborated by multiple stakeholders who are involved in its development and implementation.

CSA supports configuring globally applicable agricultural management principles to achieve food security in the context of climate change. CSA relies on three strategic management pillars: (i) sustainable improvement of agricultural productivity and household incomes; (ii) adapting and building household resilience to tackle climate change; and (iii) reducing GHG emissions [16]. In other words, CSA compiles various sustainable methods to enable the adaption of a farming community to climate change by mitigating its impacts.

Although the methodology and definition of CSA were quickly adopted and developed by international agencies, including FAO and the World Bank, many controversies have occurred around the CSA concept because of some disagreements in global policy debates related to climate change and sustainability [14]. Among these controversies may be mentioned the international carbon offset markets in CSA, which represented the largest source of climate finance at the time of the launching of the CSA concept [12]. The potential of supporting carbon mitigation in developing countries was the major focus. In fact, gaps between the global objectives for attaining sustainability in the context of climate change and national policy and stakeholder interests in these countries have led to many international initiatives to improve the adoption and implementation of CSA under the conditions of different country conditions. Special efforts in these countries are deployed to promote the battle against poverty and climate change involving the mitigation of adverse effects and adaptation. So far, achieving CSA in disadvantaged countries mainly focuses on water, energy, and food [17]. Plant protection in relation to climate change and sustainability still needs to be emphasized.

2.2. Climate Smart Pest Management (CSPM)

Although CSA is well described and promoted by the FAO, the term CSPM is not commonly used in the literature. The climate-smart approach of pest management in CSA is generally referred to as a strategy of integrated pest management (IPM). FAO has defined IPM as "the careful consideration of all available pest control techniques and subsequent integration of appropriate measures that discourage the development of pest populations and keep pesticides and other interventions to levels that are economically justified and reduce or minimize risks to human health and the environment" [18]. Agricultural practices related to the IPM are based on rational and limited uses of chemical pesticides to reduce their impact on the environment and human health [19]. The proper description of the CSPM concept was recently developed by Heeb et al. [20]. Sekabira et al. [16] claimed that effective climate-smart agriculture must be compliant to climate-smart integrated pest management (CS-IPM) and, hence, they used the term CS-IPM. More recently, a research article entitled "CSPM" has described optimal pest control dynamics during a growing season in order to tackle costs due to losses in lentil production caused by pea aphid infestations as a case study [21]. The issue of crop disease management in the context of climate change is still being treated under different terms. For example, Richard et al. [5] reviewed the control of crop diseases to deliver climate-smart farming systems for low- and high-input crop production through Integrated Crop Management (ICM). ICM was initially launched in 1993 to define "the integrated pest management in a wider context that includes crop plant breeding and general husbandry as well as pests and disease control" [22]. The use of different terms to designate pest management through a smart climate approach can create challenges in knowledge mobilization and adoption of changes that are based on scientific findings.

The CS-IPM, or simply CSPM, is a newly introduced term to update an old concept of integrated pest management under climate change using smart techniques to achieve sustainable development goals. Therefore, CSPM encompasses a set of interdisciplinary approaches and strategies needed for primary production in adapting to a changing climatic environment. Accordingly, knowledge about pests' biology and techniques to control these pests must be synchronized, with effective and low-cost strategies, to minimize damage to humans and the environment. More practically, Egan et al. [19] defined the CS-IPM as an integrated approach that implements conservative and naturally compatible practices to control insects, pathogens, and weeds. With a minimum dependence on chemical pesticides, CS-IPM may subsequently reduce damage to human health, agrobiodiversity, and ecosystems. Among these practices used in CSPM, biological formulations or biologically-based methods for pest control and suitable crop varieties are the most promising sustainable alternatives [20].

3. Phytosanitary Issues Related to Climate Changes

Unexpected climate changes such as higher temperatures, water shortages, rising sea levels, the disruption of ecosystems, and the loss of biodiversity are indirectly affecting the health of rain-fed crops and forage by reducing water availability, inducing drought and salt stress, limiting nutrient uptake from the soil, and degrading land [5]. In the disease triangle, abiotic environmental factors are extremely important in determining the susceptibility of crops to diseases involving stressful conditions affecting the normal growth and tolerance of plants to the presence of pathogens [23]. From excessive or deficient water to strong storms and forest fires, extreme weather events are generating physical damage in plants, rendering crops more vulnerable to pest attacks; hence, the disease expression or infestation can be much more severe compared to stable conditions [24]. Environmental factors may also induce favorable conditions for the occurrence of infections [25]; therefore, the magnitude and speed of climate change are involved in the creation of new disease and pest scenarios that can directly affect crop health. Global warming initiates ecological changes which modify the biology, population shape, and distribution of many microorganisms and insect species (Table 1). Consequently, phytosanitary problems are likely to become less predictable and more difficult to treat [26].

Table 1. Examples of climate change impact on plant pests.

Pest Species	Region	Changes	References
European spruce bark beetle (*Ips typographus* Linnaeus)	Norway	Two generations are recorded in forests instead of one generation per year due to warming	[27]
Old World bollworm (*Helicoverpa armigera* Hübner)	United Kingdom and the northern edge of its range in Europe	Extension of geographical distribution from 1969 to 2004	[28]
Oak processionary moth (*Thaumetopoea processionea* Linnaeus)	Central and Southern Europe, Belgium, Netherlands, and Denmark	Geographical region extension: from Central and Southern Europe to Belgium, Netherlands, and Denmark	[28]
Nun moth (*Lymantria monacha* Linnaeus) and the Gypsy moth (*Lymantria dispar* Linnaeus)	Europe	Extension of the northward shift distribution range (approximately 500–700 km) and retraction of the southern edge ranges by 100–900 km	[29]
Wheat yellow rust (*Puccinia striiformis* Westend)	Northern Indian state of Punjab	Emergence of a new pathotype which can cause infection in late December due to higher temperatures	[30]
Phytophthora infestans	Western Europe	Local thermal adaptation with invasive behavior linked to increased aggressiveness	[31]

By disrupting natural ecosystems, climatic changes seem to be responsible for new disease scenarios observed recently, as described in Figure 1. The emergence of new diseases or the introduction of new pests into a region can be the worst scenario related to climate change. Global exchanges and trade are the main cause of the introduction of new pests and diseases to a new area. These newly introduced diseases may become epidemics as changing climatic conditions are providing favorable conditions for their establishment and spread into non-native areas [32]. Although these pests/pathogens are not considered determinants in their natural ecosystems, they may cause serious drawbacks in a new environment, given that naturally occurring predators of such pests may not be present and host plant species may not have acquired appropriate defense mechanisms against the aggressor [24]. For instance, the introduction of the pine wood nematode (*Bursaphelenchus xylophilus* (Steiner and Bührer) Nickle), to Japan in the early 1900s caused serious damage to pine trees, with an annual loss of 2.4 million m^3 [33], even though this nematode is not considered to be devastating in its native region of North America [34]. A more recent example of pests that have already expanded their distribution and host species due to climate change is the red palm weevil (*Rhynchophorus ferrugineus*). The red palm weevil was first detected on date palms in the Near East in the mid-1980s. Today, the red palm weevil infests various palm species, including coconut, and had expanded to the Near East, Africa, Europe, and the United States of America (before its eradication in 2015) [2]. Another example that can also be cited here is the enormous outbreak and damage of the Mediterranean bark beetle population size (*Orthotomicus erosus*) in Croatia [35]. Xylella fastidiosa, the causal agent of several bacterial diseases in many crops, is a recent example of how the pathogenicity can change once the pest is introduced into a new environment. *X. fastidiosa* was described as an endophytic bacterium native to Central America for decades before being recently detected in several regions outside of these regions and a source of worldwide concern due to global warming [36]. The bacterium was first detected on olive trees in the southern part of Italy in October 2013 [37]. Genetic analyses suggested that this bacterium was accidentally introduced from Costa Rica or Honduras via infected ornamental coffee plants [38]. Since then, *X. fastidiosa* has spread to other zones of the European Union and has caused a rapid decline in olive tree plantations [39]. Although the risk of introduction and establishment of *X. fastidiosa* in the Near East and North Africa (NENA) countries is high due to trade, favorable weather conditions, and the high prevalence of host plants and insect vectors, the bacterium has so far not been detected in these regions [40,41]. Intensive national and international actions carried out by many organizations such as FAO, International Plant Protection Convention (IPPC), International Centre for Advanced Mediterranean Agronomic Studies (CIHEAM), and National Plant Protection Organizations (NPPOs) to prevent the introduction and spread of *X. fastidiosa* in NENA countries [42] should also be highlighted as one of the reasons for the absence of this disease in these regions. Another example of how much climate change can accelerate the threat of plant disease is the new strain of Panama disease *Fusarium oxysporum* f. sp. cubense (known as "TR4") in banana crops that appeared in the 1960s in Taiwan and rapidly spread throughout the world's Cavendish banana growing regions [6].

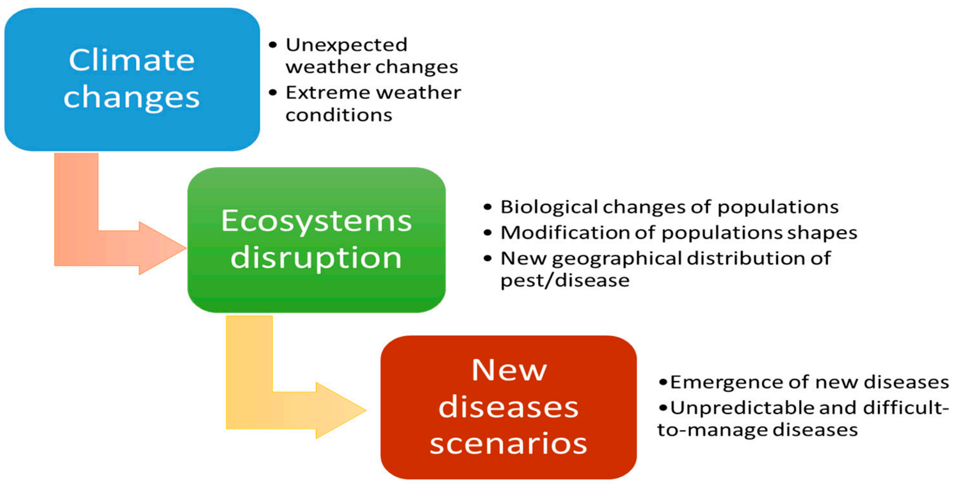

Figure 1. Relation between climate changes and new plant disease scenarios.

4. Role of Climate-Smart Pest Management in Promoting Sustainability

Since disease scenarios are being shaped by climate changes, pest management strategies will have to be adapted to weather fluctuations. The CSPM pyramid consists of three main processes which include risk assessment and forecasting, early diagnosis, and efficient interventions (Figure 2). However, preventive actions for pest control are always required to increase the efficiency of each process.

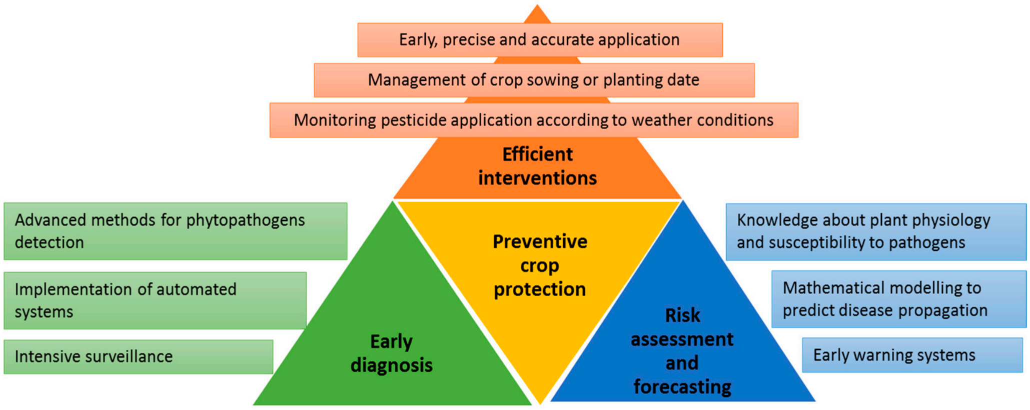

Figure 2. Pyramid of the CSPM main processes in sustainable agriculture.

Preventive measures in plant protection are very important because they maintain the level of pests and plant pathogens below the control threshold. Preventive crop protection involves the use of appropriate plant materials (certificated seeds, cultivars with high tolerance/resistance to pathogens), promoting natural enemies, etc. Starting crop production with pathogen-free seeds is the best way to protect cultures. Rotating crops may also help to break the cycle of infection and, thus, reduce the inoculum density in the soil. Many soils facilitate the persistence of soil-borne pathogens for many years, making these soils unsuitable for susceptible crops [43]. Breeding plants with those that are genetically disease-resistant is another way to prevent diseases. Plant breeding may be coupled with the breeding of natural enemies or biocontrol agents to have synergetic effects and to select biocontrol organisms adapted to the crop that they should protect [44]. Breeding in the context of CSPM may be challenging in terms of making predictions of the adaptations of the biocontrol agents or the selected plants to climate change. For example, stress due to acute changes in the abiotic conditions may affect the response of plants to current pests [45]. Therefore, crops with higher degrees of phenotypic plasticity tolerating varying environmental contexts may be an effective strategy to increase the resilience of agricultural systems to climate change [46]. Preventive measures in plant protection also include cultural practices. For example, choosing the best time for seeding or planting may be critical when cropping under changing weather patterns to prevent diseases [47].

4.1. Risk Assessment and Forecasting

Understanding the effect of climate change on pest biology and epidemiology is crucial for risk forecasting and analysis. To achieve appropriate pest control, CSPM programs are managed to prevent the appearance and development of pests and monitor predicted outbreaks. Risk assessment and forecasting involve the use of early warning systems that provide information about disease prevalence, appearance, and progression related to weather data. Knowledge about plant physiology and susceptibility to pathogens can help to determine timeframes where plants are most susceptible to pathogens. Mathematical models are always conceived to predict disease propagation [48,49]. Studying meteorological factors is crucial, not only for forecasting pest fluctuations but also for inferring the area with suitable climate conditions and visualizing maps to estimate regions for the potential establishment of diseases and assisting outbreak response programs [41]. Therefore, countermeasures can be undertaken to suppress pathogen severity through early treatments or preventive interventions such as changes in planting dates, rotating between crops, and other cultural practices. Forecasting and early warning systems have been developed with the appearance of computer technology and software [50]. Many disease-warning systems based on weather conditions have been developed and validated for dozens of crops in the recent decades (Table 2). However, many other models are still needed to improve accuracy, given the complexity of climatic and landscape factors. For example, the effect of weather conditions and spatial factors on the geographic distribution of *X. fastidiosa* were studied using the outbreak in Alicante, Spain, through stationary and nonstationary models [51]. Nevertheless, non-stationary models are still to be improved with more methodological research to obtain more realistic models, since the study assumes that barriers are completely impermeable to the pathogen spread, as mentioned by Velasco-Amo et al. [41], which is not the case for *X. fastidiosa* and the majority of plant disease agents.

Table 2. Historical examples of disease warning systems (according to [50] with modifications).

Crop Disease Warning System	Aim	Reference
TOM-CAST	Providing data for processing-tomato growers once per week during the first month of the growing season and three times per week after fungicide sprays began	[52]
SkyBit Inc.	Site-specific estimation of weather conditions and pest risks in near-real time, and forecasting up to 3 days in advance at a spatial resolution of about 1 km^2	[53]
A network of more than 2000 automated weather stations of private farm management companies	Providing color-coded regional risk maps across the western United States for targeted agricultural risks, pests, and diseases (12 diseases and six insect pests)	[54]

Some sources emphasize the importance of public contributions to the early detection and reporting of emerging plant health threats through passive surveillance programs and citizen science (vigilance) [55,56]. However, we think that to succeed in the establishment of such new programs based on public observations and reports, more effort must be invested in well-conceptualized analytical methods that serve as useful tools to manage putative uncertainties and assess these unstructured data.

4.2. Early Diagnosis

Disease diagnosis is a fundamental process in CSPM starting from surveillance to pest identification. To allow adequate disease management actions with fewer damages to the environment and health, constant surveillance activities are required to detect newly introduced pests and/or pathogens [28]. Surveillance is also an important tool in the declaration of pest and/or disease-free areas or areas of low pest and/or disease prevalence, an important classification that is used in trade certification [24].

Phytopathogen diagnosis techniques are becoming rapid and reliable in the detection, quantification, and identification of plant diseases even to the strain level, which facilitates early and accurate interventions for disease control. Early plant disease diagnosis is based on fast and sensitive technologies of nucleic acid, biosensor, and protein analysis as advanced methods allowing the detection and quantification of phytopathogens [57]. Highly sensitive molecular diagnostic tests (to the strain level in some bacterial diseases) had improved subspecies and geographical origin assignment of many diseases as shown in the study of crown gall recurrent infestations in Tunisia caused by contaminated plants [58] and the quick decline of the syndrome caused by *X. fastidiosa* by the recent outbreak in the olives [41]. Real-time PCR, next-generation sequencing, and fluorescence in situ hybridization techniques can detect phytopathogenic micro-organisms on asymptomatic vegetation and vectors before their transmission to the plants, such as in virus diseases [59]. Therefore, maintaining state-of-the-art diagnostics as well as toxicological laboratories is essential in the early diagnosis process.

In the last decade, several non-invasive techniques, including spectroscopy-based, imaging-based, and relevant remote sensing methods, have also been developed [60]. These techniques promote the real-time and large-scale detection of plant diseases. Other than the common advantages of non-invasive techniques, their implementation in automated systems is resulting in a considerably reduced workload compared to molecular and protein analysis [61]. The early detection of viral diseases has become possible with spatial and temporal thermography patterns, such as in the case of the tomato mosaic virus where the infection had been detected five days before the appearance of symptoms [62]. More recently, implementing remote sensing techniques with drones has enhanced the prospection of infestations in fields [63]. Drone sensing is effective in saving time, allowing broader surface coverage, and improving spatial image resolution.

4.3. Efficient Interventions

Appropriate decision-making for any interventions in CSPM must be ecologically and economically justified [20]. Therefore, pest control programs involve environmentally friendly approaches aiming principally to reduce the use of chemicals for more sustainable agricultural systems and increase food safety. Preventive methods and alternative control techniques with efficient and low-risk effects are considered first in CSPM. Eco-friendly methods include targeted and biocontrol alternatives such as pheromones, mechanical trapping methods, biological molecules, antagonistic organisms, etc. [64].

Biocontrol agents related to weather changes involve new climate-resilient strains with the highly competitive ability needed to survive in the introduced environment. Furthermore, region- and crop-specific strains are integrated into the CSPM approach [65]. The sowing or planting date of crops may be also managed according to new disease scenarios related to climate change. Temperature fluctuations and variable rainfalls have impacts on pesticide residue dynamics, including retention of contact, wettability, atmospheric distribution, product degradation, etc. For example, González et al. [66] reported the impact of temperature and time on the amount of fungicide and its translocation into individual turf grass plants following application. Consequently, monitoring pesticide application according to weather conditions promotes efficient interventions.

In the past decade, pest treatments are being scheduled according to climate variables in several countries (Table 3). Moreover, targeted treatments are based on smart agriculture technologies including optical and thermal sensors. These sensors can detect early changes in plants once they are under biotic stress because diseases can induce several modifications, such as leaf shape and color, transpiration rates, plant densities, light reflectance, etc. [67]. The precise localization of a diseased plant's spot, with accurate imaging data, is useful in targeted treatments and the calculation of the required pesticide quantity [68].

Table 3. Monitoring of phytosanitary treatments according to weather conditions.

Diseases/Pests	Decision According to Weather Changes	References
Wheat blotch (*Septoria tritici*)	The decision system for the timing of fungicide application has been made based on different climate variables in the United Kingdom.	[69]
Potato late blight (*Phytopthora infestans*)	In the northeast United States, the susceptibility period of the disease would be raised by 10–20 days due to temperature increasing. A need for an addition of 1–4 fungicide foliar applications was predicted.	[70]
Stem rot of peanut (*Sclerotium rolfsii*)	Fungicide application early in the morning to improve spray deposition in the lower canopy of the plant	[71]
Lepidopteran insect pests	– New York conditions currently require 0–5 insecticide applications – Maryland and Delaware conditions require 4–8 insecticide applications – Florida conditions require 15–32 applications	[69]

Efficient application of chemical products cannot only alleviate environmental and health damage but also can reduce resistance development related to repeated pesticide exposure. Furthermore, pesticide treatments can be sprayed with the use of drones, which decreases chemical exposure of the operator and reduces pesticides drift [72].

4.4. Zero-Tillage Potato IPM for Climate Mitigation as a Successful CSPM Story

Rice-based systems appear to be the main challenge in sustainable intensification in Asia. Several studies have discussed problems related to carbon emission from rice-residue burning, excessive use of pesticides, the overexploitation of water for irrigation, and land degradation in such agricultural systems in Asia [73]. The implementation of sustainable intensification practices into rice lands has been reported as promising solution for climate change mitigation. Diversification with potato cultivation under no-tillage and/or organic mulching with rice straw has recently been recognized as a success story on multiple levels after being implemented through various actions in Asia [74,75], even in saline soils [76].

This successful CSPM story took place when FAO initiated an innovative pilot project which promoted the sustainable rice–potato farming system carried out in Thai Binh, a Vietnamese Province, from 2009 to 2011 [74]. This system consists of "zero-tillage potato IPM" as named by the FAO, where potato seed tubers were directly placed on the beds created by drainage grooves and mulched with straw left over from the rice harvest, without tillage. After a series of research, this zero-tillage practice showed promising results for climate mitigation on different levels compared to the traditional tillage practice of soil-mulched potatoes. Mainly, the use of the leftover rice straw to cover potato seed tubers reduced the need for irrigation (from 5000 m^3/ha of water to only 900 m^3/ha) and gas emissions, because rice straw was burnt in traditional practices. Farmers are used to burning crop residues in order to shorten their long decomposition period and to prevent the spreading of diseases from the previous harvest [77]. More importantly, this practice has shown that the straw mulch could generate functional biodiversity that plays an important role in pest management. Straw mulch is known to create an environment of optimal temperature, humidity, and organic matter favorable for the development of beneficial microflora in the soil [78]. Furthermore, the application of straw mulch can suppress and reduce weed growth by limiting resources [75]. Although tillage may play an important role in controlling weed populations [79], in this case, mulching seems to be more efficient since it led to a 50 percent reduction in herbicide use compared to the amounts that are typically used in the conventional tillage system, as reported by the FAO [74]. Since farmers are used to applying more pesticides in response to the spread of invasive plant pests and disease species promoted by climate change in Asia, this practice could help to protect the health of smallholder farmers and their environment.

This innovative technique has so far been promoted in several rice-dominant Asian countries and has achieved important environmental and socio–economical gains. For instance, potato cultures using few inputs and residues from the previous crop without tillage are used for sustainable intensification and diversification of cereal-based cultures in India and Bangladesh [80].

5. Challenges of Climate-Smart Pest Management

Being a component of CSA, CSPM shares the same issues related to regulations and decision-making, adaptation to regional conditions, and knowledge updating and upgrading. Although CSPM promotes actions within the context of sustainability that contribute to eco-friendly farming systems, food security, and human health, in practice, CSPM actions are not evident and are limited to regulations and decisions. The decision-making process in CSPM is highly complex and dynamic because it requires constant weather database updates of operators and tools to collect and handle data. Spatial and temporal dynamics of plant diseases according to climate changes are still poorly understood despite the existence of well-developed models for major crops and pathogens [81]. Plant disease simulations are based on multifactorial models, which makes it difficult to predict how climate variability will affect disease development and management. Although models to forecast the impact of climate on crop production have been successfully developed more than 40 years ago, the current knowledge about weather-related pests may not be valid in the future under unpredictable drastic climate events. The lack of implementation limited the transition of many agricultural decision support systems (DSS) from scientific validation to real-world application [82]. Despite the development and diffusion of information and communications technology (ICT) that has occurred over the last decades, DSS is still facing some limitations (Table 4). For example, in the last 50 years, disease warning systems have been developed and validated for dozens of crops, but the rate of farmer adoption of these models is far from satisfying. This limited implantation of systems due to the disconnection between developers and users may not meet producers' needs, which may explain their reluctance.

Table 4. Examples of some Decision Support System (DSS) limitations (according to [83] with modifications).

DSS Limitations	Examples	References
DSSs do not adequately consider all aspects of production	Several DSSs focus on saving an individual spray, but growers are usually more concerned with maintaining quality standards or meeting regulations.	[83]
Low quality of the products	Poor communication between the DSS developers and users, so that in commercial DSSs the refinement phase of the DSS products is lacking.	[83]
Lack of user-friendly interfaces	Many DSSs have presented their outputs in quantitative terms, while growers find difficulty in their interpretation.	[83]
Tedious input requirements	Much information requested as input, while farmers did not have the time to fill in the system.	[84]
Delays in data processing and/or update	Difficulties in rapidly updating the default DSS databases (e.g., climate data and PPPs) can reduce the usefulness of the system to the growers.	[84]
Maintenance costs	Difficulties in rapidly updating the default DSS databases (e.g., climate data and PPPs) can reduce the usefulness of the system to the growers.	[85]

Due to the complexity of the CSPM concept, every crop and region of a country needs specific reflection. Many growers of certain crops attempt to define appropriate pest control techniques for their crop species as well as their region of growth. Local, regional, and national conditions are different and suggest specific strategies in disease-warning systems, decision-making processes, and management methods. Even though weather data have become more accessible with cheaper and easier-to-use climate-monitoring systems, the failure of equipment due to bad positioning, sensors drifting out of calibration, and battery exhaustion is still the main origin of errors in weather data collection if it is not anticipated, prevented, or promptly solved [50].

Precision farming relying exclusively on smart technology access to the Internet and many other variables may produce vulnerable agricultural systems. Devices related to an internet connection, or the knowledge use of ICT, are not always available in the agricultural sector, especially in smallholder farms and rural communities of developing countries. As a result, CSPM in these areas may be far from feasible. Moreover, these countries lack technical capacities for phytosanitary diagnostic and analysis laboratories. Such countries with extensive land space may represent a serious problem in the world of trading when it comes to the spread of pests into new areas. Almost all the experts recommended an international collaboration and harmonization of the legislation to enhance the efficiency of CSPM in food security and safety achievement.

Obviously, the above-discussed challenges of CSPM emphasize several shortcomings of scientific findings and research results which can limit their usefulness under field conditions.

6. Research Gaps and Future Recommendations

The vulnerability of food security to crop diseases and pests has been accentuated by climate change, as explained early in this document. Although several actions have been taken on how to develop different CSPM techniques and strategies, future research is still needed to enhance their efficiency and facilitate their utilization. While the negative impact of global warming on plant health is well documented and analyzed, its negative impact on pest and pathogen prosperity has not been enough explored. For example, plant viruses could be affected indirectly by climate change once the population of their insect vectors is affected. This influence could have neutral, positive, or negative effects on the emergence and development of plant viral diseases [86]. The impact of climate change may directly or indirectly affect crop pathogens and pests by disturbing higher trophic levels through managing the development of natural enemies and physiological traits in host plants [7]. For example, the recent bark beetle outbreak in Central European coniferous forests associated with world climate changes is the cause of the creation of large clearings, resulting in a loss of food resources and, therefore, a decline of wood ants (especially Formica rufa Linnaeus) [87]. Wood ants also prey on beneficial organisms such as the parasitic flies Ernestia rudis (Fallén) whose larvae are parasitoids of other pests [88]. In this case, global change can indirectly affect the abundance of pests by affecting higher levels of the trophic system. Consequently, model conceptions based on the assessment of the whole trophic system through long-term monitoring of herbivores and phenological processes are very important to understand their response to current climate change and, therefore, to improve risk assessment systems and prevention methods. Moreover, direct and indirect negative impacts of global warming on plant pathogens and pests should be deeply explored to enhance knowledge that could develop new biocontrol techniques and strategies. Research on biocontrol agents and products, in the context of CSPM, is still very restrained. Advances in digital agriculture and the breeding of pathogen-resistant cultivars in crop production are currently the most effective strategies to prevent diseases. However, more studies on climate-smart pesticides are still required for the development of environmentally friendly new products with novel molecules/modes of action and high efficacy at low doses. The market of new molecules in pharmacology is still much more developed than agrochemical products. For example, the FDA has authorized 160 drugs in three years (between 2018 and 2020) [89], compared to only 105 chemical pesticides (most of them are safe for humans and environmentally friendly) launched during the last decade (between 2009 and 2020) [90].

Another technological challenge is how to study disease spread at the landscape scale, as it is more complex than at the field scale, with more various crops, variable hedgerows and windbreaks [91], different cultural practices, etc. Recently, some studies have used computer simulations to identify the best strategies for managing resistant cultivars at the landscape scale to ensure the durability of resistance [92,93]. However, limitations due to the feasibility and economic viability of farmers to deploy these strategies underscored the necessity for more data [5]. Furthermore, the large amount of data generated by climate-smart agricultural technologies (remote sensing, DSS, etc.) needs to be rapidly analyzed and interpreted. Some scientists have suggested machine learning and deep learning methods to resolve this problem [94,95]. Although advances in digital agriculture and the breeding of pathogen-resistant cultivars in crop production are currently the most effective strategies to prevent diseases, the increasing dependence of CSPM on new technologies could make agricultural production more vulnerable, especially in disadvantaged regions. More research should be consecrated to domain-specific issues such as web infrastructures, farmers' ability sets, and availability of smart farming-specific protection mechanisms [96] before being widely accepted [97]. To this end, more multidisciplinary experiments [5], knowledge [98], and information with a clear description should also be accessible to enable the analysis of more complex data sets and run more performed models. For instance, the European Union's "Farm-to-Fork" strategy needs to provide more ecosystems and agroecology services [99,100] to help farmers make economic decisions to choose the right pest management technique for mitigation and adaptation to climate change, as reported by Richard et al. [5]. In the same context, international research collaborations should hire in-country expertise to ensure that research is axed on national needs and that findings are well extended and communicated to all stakeholders. In this regard, national regulations should take the need for the international exchange of biological samples into consideration and be more flexible to facilitate the movement of genetic resources.

7. Authors' Perspectives

Climate changes are of global interest, and this is how CSPM should be recognized. To succeed in sustainable pest management approaches under weather fluctuations, internationally collaborative efforts are required.

First, CSPM legislation must be globally harmonized and emergency planning for plant pests must be undertaken on an international level. For example, the technical requirements of any commercial commodity must be properly described to protect a country from the potential introduction of new pests and/or pathogens and strengthen consumer confidence without any hidden purpose of promoting the competitiveness of domestic producers. Otherwise, phytosanitary legislation would be unjustified and restrict international trade.

Second, different sectors in relation to climate change should be enrolled in collaborations, including research activities for risk assessment, surveillance, and monitoring. For example, consortia of public-sector researchers, private-sector service providers, and growers could be organized for more reliable and sustained disease warning systems (proper installation and periodic maintenance of weather instrumentation, along with timely verification of weather data). Furthermore, models used in crop prediction systems should be calibrated with reliable yield data from longer periods (preferably 20–25 years).

Third, policies may be established to strengthen the uptake of different interventions and their adoption, such as CSPM crop certification systems. CSPM-grown labeled products may promote this sustainable production agrosystem and offer better choices to consumers while purchasing their food.

Fourth, more efforts are needed in developing countries for capacity building and technical assistance to ensure optimal use of resources. Countries in Africa, Asia, and Latin America are striving hard under economic constraints to ensure food security for their populations. Therefore, the lack of political will is the most important constraint to achieving a more effective research and extension system related to CSPM. International financial institutions may fund the establishment of regional laboratories or centers of excellence in developing countries to facilitate cooperation and enhance the adoption of CSPM strategies such as forecasting, surveillance, and diagnosis. More research on climate change effects on pests, diseases, and food-borne pathogens should be undertaken collaboratively to enhance the current knowledge and eliminate knowledge gaps. Small-scale farm holders and rural communities in developing countries are especially vulnerable to the impacts of climate change and, therefore, they require specific national, regional, and international political attention and additional funding to promote CSPM adoption. National and international institutions may consider some approaches adapted to these farming systems in their interventions, such as the establishment of local advisory services and crisis cells, and special allocations for CSPM funding. Moreover, the organization of periodic training courses related to risk assessment and providing tools such as smart cell phones for farmers to facilitate access to weather information may help them in disease surveillance and decision-making.

8. Conclusions

CSPM is considered an up-to-date approach that can help to transform and re-invent sustainable agricultural systems to achieve global food security and safety. CSPM strategies aim to predict changes in pest scenarios caused by climate change through intensive surveillance and forecasting systems for an early diagnosis and efficient risk monitoring interventions. Effective interventions in CSPM are based mainly on environmentally friendly management actions to ensure improved farm outputs for people and ecosystems. However, the global adoption of CSPM requires more coordination and collaborations of multi-sectoral consortia to especially upgrade the existing knowledge about the effect of climate changes on plant diseases and facilitate the decision-making process as well as alignment of policies. Developing countries may represent the weakest link in this chain, where the CSPM implementation needs intensified efforts from the international community. Impediments caused by climate change in these countries have more serious drawbacks on agricultural resources in the absence of proper pest management strategies and technologies. Politicians' vision, regional institutions, farmers' socioeconomic and biophysical contexts, and characteristics of the new technology, among others, are vital determinants in the implementation and adoption of CSPM in these societies.

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