Article

Implementation Outline of Climate-Smart One Health: A System-Thinking Approach

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Abstract: The One Health (OH) concept has evolved significantly in recent decades, emerging as a key framework guiding international research and policy in managing new infectious diseases, chiefly zoonoses. While its initial conception revolved around managing zoonotic diseases as they traverse the interface between animals and humans through the environment, this concept has transformed beyond its origins as a collaboration solely between veterinary and public health stakeholders. Notably, the past decade has ushered in a new era of addressing complex issues in a novel manner. Emerging evidence has led to a fresh theoretical framework, highlighting interconnected terrestrial and aquatic ecosystems. Understanding these links is crucial in tackling emerging issues and resultant health challenges within these systems under what we call One Health 2.0. The current paper describes Climate-Smart One Health (CS-OH) and Climate-Smart Integrated Pest Management (CS-IPM) approaches, emphasizing holistic perspectives and practical tools. The One Health (OH) 2.0 concept applies to the agricultural sector and more specifically to agrifood systems exposed to climate change impacts. It is meant to address, in a comprehensive manner, soil, water, plant, animal, rural and urban farmers and farming communities, and consumer health issues. The One Health (OH) 2.0 concept is embodied in the Climate-Smart One Health (CS-OH) approach. The latter is designed for applications in agrifood systems. Pathways for the deployment of both CS-OH and CS-IPM interventions are proposed in this paper. A Ghanaian case is discussed.

Keywords: climate change; complex problems; holistic approach; smart tools; policy advocacy

1. Introduction

1.1. Context and Definitions

In recent years, the world has witnessed various health concerns, causing havoc on people's well-being. A series of infectious diseases including zoonoses and the additional burden of coronavirus disease 2019 (COVID-19) has put humanity at serious risk in terms of health [1]. This health crisis has compromised the livelihoods of earth inhabitants from multiple sectors, including agriculture [2]. The agricultural sector is one of the most exposed to risks contingent to the climate and other factors including pests, diseases and mycotoxins; logistics; finance; and markets [3,4]. This paper describes a complex climate–OH nexus issue in farming systems.

One Health (OH) is referred to as per a selected set of definitions among the wide range of existing narratives of the topic [5]. One Health is a collaborative effort of multiple health science professions, together with their related discipline and institutions—working locally, nationally and globally—to attain optimal health for people, domestic farm and food animals, wildlife, plants and our environment [6–8]. Another close definition that speaks to an integrated concept of OH stands for a collaborative, multisectoral and transdisciplinary approach—working at local, regional, national and global levels—with the goal of achieving optimal health outcomes recognizing the interconnection between people, animals, plants and their shared environment [8]. The approach is holistic and embraces multiple sectors, disciplines and communities at varying levels of society to work together to foster well-being and tackle threats to health and ecosystems, while addressing the collective need for clean water, energy and air and safe and nutritious food, taking action on climate change and contributing to sustainable development [9]. All of the above definitions were quoted as per their original statements to avoid misleading content. There is increasing evidence that human pathogenic diseases can be aggravated by climatic hazards [10]. Such evidence is highlighted and put into the OH perspective in this paper.

To feed the ever-growing global population of humans, food systems need to transition to their optimal and most resilient potential under pressing changing climates, while safeguarding natural resources such as soil, water and genetic resources [11]. Climate-Smart Agriculture (CSA) is driving increasing interests among agricultural stakeholders to tackle the above-mentioned challenge in order to sustain revenues, achieve communities' resilience to climate shocks and stimulate economic growth. CSA prioritizes and integrates a range of agricultural innovations that contribute to increased productivity and resilience of food systems, while increasing carbon stocks and reducing greenhouse gas (GHG) emissions. The concepts Climate-Smart One Health (CS-OH) and Climate-Smart Integrated Pest Management (CS-IPM) have evolved from their root anchorage of Climate-Smart Agriculture (CSA). They are meant to unlock CSA benefits for optimal OH (CS-OH) outcomes in farming communities or IPM (CS-IPM) targets in agroecosystems.

Infectious diseases affecting humans, and crop's pests and diseases bear huge human capital and economic costs [12], particularly in a scenario of poor prevention and lack of preparation. Early Warning and Rapid Response (EWRR) involves monitoring, surveillance, forecasting, predicting, reporting and responding to specific risks in a very well-coordinated manner within an institutional framework [13–15].

1.2. Advancing the One Health Concept: Addressing Challenges and Opportunities in a Changing World

Over the past decades, the One Health (OH) concept has emerged as a pivotal framework guiding global research and policy efforts, particularly in managing novel infectious diseases, primarily zoonoses [16]. The OH approach involves multidisciplinary collaborative efforts to attain optimal health for humans, animals, plants and the environment on local, national, regional and global scales [17]. In its original conception, OH centers on the interaction among humans, livestock and wildlife [18]. Nevertheless, the scope has broadened over time to encompass a comprehensive approach to tackling urgent societal challenges. This approach implicates health considerations for soil, water, air, plants, ani-

mals and humans. Notably, this expansion has sparked further growth and contemplation within food systems, which face intricate challenges posed by climate change [19]. Added to this is the need to feed a growing population, which requires increased productivity and reduced pre- and post-harvest losses. In addition, efforts to attain increased food production should consider environmental quality priorities. As a result, the OH concept has given rise to initiatives to mitigate biological risks and effectively manage their impact. These initiatives involve early and swift detection and data collection to facilitate integrated risk monitoring and prevention [17]. Nevertheless, despite the growing dedication to OH initiatives globally, putting OH approaches into practical action remains challenging. For instance, many countries lack formal mechanisms for coordinating and integrating OH endeavors across human health, agricultural and food systems, and the environment. Traditionally, these sectors fall under distinct government ministries or agencies, each with disparate responsibilities and budgets [20]. OH practices within these agencies are also confronted with challenges, including the need to bridge disciplinary divides and foster knowledge sharing among various stakeholders with different backgrounds and interests, such as scientists, regulators, farmers, industrialists and consumers, among others [21].

The original concept of OH solely focused on managing zoonotic diseases, which transfer from animals to humans through the environmental interface. This concept initially involved collaboration primarily between veterinary and public health stakeholders. The notion of environmental or ecosystemic interactions affecting both animal and human health encompassed several interconnected elements that were not fully disclosed at the time. However, over the last decade, there has been a fascinating emergence of a new OH approach to addressing complex issues. The emergence of evidence supporting a novel OH theoretical framework has spurred new investments to comprehend the interconnections across terrestrial and water ecosystems [22–25]. This understanding aims to tackle emerging issues within these systems and the health challenges they present to various elements within the ecosystems [26]. While this emphasis remains fundamental, the expansion of OH to encompass wider communities, landscapes and urban environments signifies a profound recognition of the complex interconnectedness that defines our world and the multifaceted challenges we face. This evolution extends OH's scope beyond the traditional animal–human interface, placing heightened importance on the health of ecosystems themselves.

Ecosystems provide indispensable services such as clean air, water purification and climate regulation, directly influencing the well-being of communities and urban centers [27,28]. The state of these ecosystems is intricately tied to health outcomes. For instance, the degradation of natural habitats can increase the risk of zoonotic disease spread, whereas undisturbed ecosystems can act as protective buffers [29–33]. Furthermore, with the majority of the global population now residing in urban areas, OH adapts to address the unique health challenges posed by urbanization, encompassing issues of overcrowding, sanitation, and healthcare access [34,35]. OH also extends its purview to encompass the entire food production and distribution chain within our increasingly complex and interconnected food systems, recognizing the profound health and environmental consequences associated with our dietary choices [36]. Climate change, with its far-reaching implications for disease patterns, food security [37] and the availability of clean water, assumes a central role within OH's expanded framework [38]. Finally, in our highly interconnected world where goods, people and diseases crisscross the globe with unprecedented speed, OH underscores the critical importance of global health security, emphasizing collaboration and information sharing as fundamental tools for effectively responding to emerging threats [39].

1.3. Challenges of Climate Change and Weather Variability in Africa

The challenges posed by climate change and weather variability in Africa are undeniably pressing [40,41]. These environmental shifts have cast a shadow over the agricultural landscape, affecting both pest and disease dynamics as well as crop productivity [42,43]. Irrespective of their agroecological locations, farmers have keenly felt the repercussions of climate change on their agricultural practices and on the overall yields. The rising tempera-

tures and erratic rainfall patterns have left an indelible mark on the agricultural outputs, with significant consequences reverberating across Africa [44–47]. One stark result of these changing climate conditions is the proliferation and survival of Invasive Alien Species (IAS) in previously uncharted territories [48–50]. Several machine learning algorithms and mathematical models have predicted potential distribution shifts of poikilothermic organisms such as agricultural insect pests under different climate scenarios. For instance, a case study on the fall armyworm (FAW) *Spodoptera frugiperda* (Smith) (Lepidoptera: Noctuidae) projects that the pest's invasive range will retract from northern and southern regions of Africa towards the equatorial ecologies [51]. Another report showed that suitable areas for the tephritid oriental fruit fly *Bactrocera dorsalis* (Hendel) will increase, with the distribution range expanding northwards in future climate scenarios [52]. These pests are often associated with huge losses in the event of outbreaks, thereby having massive consequences in terms of food and nutritional insecurity and bearing socioeconomic costs worth billions of US dollars per annum [53]. The first-resort management scheme of most instances relies on synthetic pesticides, although there are cases of inappropriate use and fraudulent utilization of highly toxic active ingredients, posing threats to the soil, water, and farmer and consumer health and raising biodiversity risks (e.g., insecticide and antimicrobial resistance and threats to pests' natural enemies, water food, and food animals). Equally, much of the literature demonstrates linkages between the climate (basically temperature- and humidity-based bioclimatic variables) and the spread of zoonotic and other infectious diseases, with a plethora of examples, including monkeypox, Rift Valley fever (RVF), hemorrhagic Ebola viral disease (EVD) and COVID-19 [54–61].

Therefore, the expansion of OH to encompass climate considerations and ecosystem interconnections represents a crucial evolution in response to these multifaceted challenges. Climate change is profoundly reshaping our planet's ecosystems, exerting intricate effects on the health and well-being of humans, animals and the environment. This expanded OH framework acknowledges the urgent need for a system thinking approach to comprehensively address these interwoven issues. It recognizes that isolated, sector-specific approaches are inadequate in the face of such complexity. The tricky web of challenges posed by the complex interplay between climate and OH issues is multifaceted. These challenges emerge from the deeply intertwined interactions and feedback loops among a myriad of environmental, biological and socio-economic factors [62]. To tackle them effectively, we propose a comprehensive framework that extends beyond addressing immediate consequences. Instead, it delves into the systemic impacts and time delays inherent in each connection and the links between the elements and components of the holistic system [63]. Consider, for example, the ramifications of climate-related issues, such as the frequency of extreme weather events and unpredictable variations in rainfall [64]. These environmental upheavals have far-reaching consequences, seriously affecting ecosystems and, in turn, human and animal populations. Consequently, the essence of OH comes to the fore, emphasizing the intricate interconnectedness of human, animal and environmental health. This accentuates the pivotal importance of comprehending the complex feedback loops and relationships within the multifaceted system [62,63]. Addressing the entangled challenges of the climate and OH necessitates a paradigm shift towards holistic system thinking. This approach acknowledges that the repercussions of our actions ripple through the entire interconnected web of life, underlining the significance of adopting comprehensive strategies to safeguard the well-being of our planet and its inhabitants [65].

The side-effects of agricultural intensification or what we might call "agricultural mal-intensification" [66–68] and many other issues add to the burden of the above climate-related and OH challenges across food systems. These include increasing concerns of land degradation, reductions in biological diversity, soil infertility, the depletion of water resources and the rising invasion of alien weeds and crop pests. While agricultural intensification promises to meet the growing global food demand, it unfortunately bears some potential environmental costs. All these problems cannot be addressed in a business as usual manner, which points to the need for a mindset change and paradigm shifts.

1.4. Charting a Path towards Climate-Smart One Health and Integrated Pest Management

Within the dynamic landscape of the evolving OH paradigm, research efforts assume a central role. We are driven by the overarching objective to unravel the intricate principles and practical applications of Climate-Smart One Health (CS-OH) and Climate-Smart Integrated Pest Management (CS-IPM). These innovative approaches hold the promise of offering holistic solutions to the complex interplay between climate dynamics, health outcomes and environmental factors. We seek to shed light on how these pioneering approaches can not only be understood but effectively put into practice. Through the current research, we aim to provide a comprehensive roadmap, to be a guiding beacon for decision-makers, practitioners and dedicated researchers. Our intention is to equip them with the knowledge and tools required to navigate the multifaceted challenges presented by a changing climate while simultaneously safeguarding the health and resilience of ecosystems and the communities that rely upon them. In our quest to achieve this objective, we adopt a comprehensive perspective. The research methodology enables us to thoroughly evaluate the complex interactions among climate dynamics, health outcomes and environmental factors. This holistic perspective opens avenues to pinpoint pivotal intervention areas, offering a path towards effective solutions. However, we acknowledge the inherent complexity of these challenges. Their complex nature necessitates interdisciplinary collaboration, a commitment to sharing data, and a shared understanding of their multifaceted dimensions. This study goes beyond theoretical insights; it offers a pragmatic blueprint for the implementation of CS-OH and CS-IPM innovations. Furthermore, we share valuable lessons drawn from our experiences in Ghana, during the implementation of the Accelerating Impacts of CGIAR Climate Research for Africa (AICCRA) project, illustrating the tangible successes and the invaluable knowledge gained along the way. The current research endeavors to illuminate the path towards achieving harmony between human, animal and environmental health in an era of climate change, facilitating a brighter, more sustainable future for all. It is a pioneering ideation work of the One Health 2.0 concept under an overall Climate-Smart One Health model and under the assumption that the holistic framework proposed would inform further models and efforts to address complex issues of climate–OH-related risks.

2. Materials and Methods

2.1. Concept and Data Requirements for CS-OH and CS-IPM

Climate change presents unprecedented challenges to ecosystems, agriculture and public health, and in response, innovative solutions like CS-OH and CS-IPM have emerged as guiding lights. These frameworks signify a paradigm shift in how we address the complex interplay between climate dynamics, pest management and the overall health of the environment and communities. CS-OH and CS-IPM frameworks are characterized by their emphasis on collaboration, data-driven decision-making and adaptability, offering a promising roadmap for safeguarding the welfare of humans, animals and the environment in a rapidly changing world.

CS-OH and CS-IPM draw strength from a diverse array of datasets essential for effective risk management within the context of climate change. These datasets encompass a wide spectrum, ranging from climate data that illuminate climate-related influences on pest and disease dynamics to data on bioecology, which aid in monitoring changes over time. Information on pest–plant interactions is crucial for understanding the intricacies of pest outbreaks and crop damage, while environmental variables such as soil characteristics and land use provide insights into the ecological context in which pests thrive. Data on disease and health are indispensable, particularly for zoonoses, enabling assessments of health risks and connections between human, animal and environmental health. Additionally, ecosystem health indicators help evaluate the resilience and functionality of ecosystems, and climatic projections allow for anticipatory measures in the face of shifting pest and disease dynamics. Finally, remote sensing data provide a comprehensive view of environmental conditions that influence pests and diseases and their habitats. These datasets collectively

form the bedrock of comprehensive zoonotic and pest risk management strategies within the Climate-Smart OH and IPM frameworks, offering holistic solutions to multifaceted challenges. While the proposed dataset as a whole would provide valuable insights in the form of key factors and variables explaining the functionalities and cost–benefit features of CS-OH and CS-IPM, they were not all fully accessed and used during this exploratory ideation design work.

2.2. Design of Climate and Environmental Smartness of One Health

Three major hazard types are highlighted in the current One Health 2.0 model: biological, environmental and climate hazards (Figure 1). The rationale behind adopting the new model is firmly rooted in the following reasons. Firstly, addressing zoonotic disease issues without clear consideration or integration of climate change dimensions has increasingly proven both ineffective and inaccurate [69–71]. Secondly, overlooking climatic and environmental risks weakens the outcomes of OH (animal–human) initiatives. Therefore, integrating climate and environmental smartness has become imperative for ensuring successful improvements in OH outcomes. Various parameters can be estimated to inform climate smartness and OH 2.0 significance. Climate smartness is measured vis-à-vis productivity (e.g., output yield, marketable yield, value of labor, income), adaptation (e.g., food access, female labor, resilience) and mitigation (carbon dioxide emissions, nitrous oxide emissions, methane emissions, soil organic carbon, plant biomass) indicators. The OH 2.0 outcome is assessed using soil, water, plant, animal and human health indexes. The two sets of indicators can frame measurements and the monitoring and evaluation efforts of Climate-Smart One Health (CS-OH) operations.
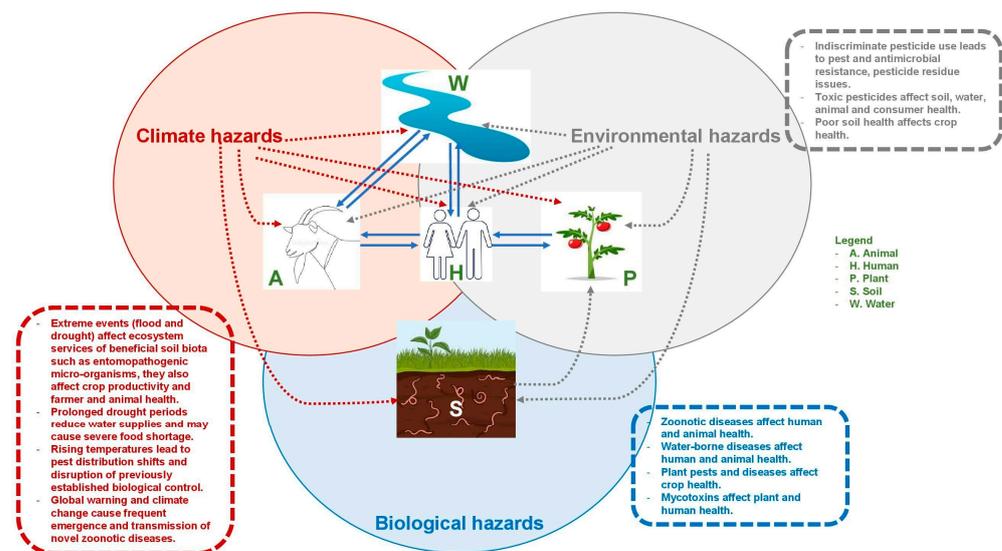

Figure 1. A comprehensive description of the One Health 2.0 concept that encompasses the interconnections between biological-, environmental- and climate-related challenges and hazards (source from Sekabira et al. 2023, [72]).

2.3. Core Pillars for Implementing Climate-Smart One Health

The Climate-Smart Agriculture (CSA) scheme constitutes the foundational stone of the Climate-Smart One Health (CS-OH) approach. The core elements of CSA contributing to the CS-OH goal are highlighted in Figure 2. Incorporating an OH intervention within a Climate-Smart Agriculture (CSA) framework renders the CS-OH approach, signifying that specific CSA technologies or innovation packages enhance OH outcomes. For instance, the utilization of biorationals and biopesticides and organic farming (e.g., Black Soldier Fly BSF-made fertilizers and larval feed for fish and poultry) for premium-quality produce can potentially contribute to both triple-win CSA and plant health, while safeguarding the health benefits of soil, water, animals and humans (Figure 2).
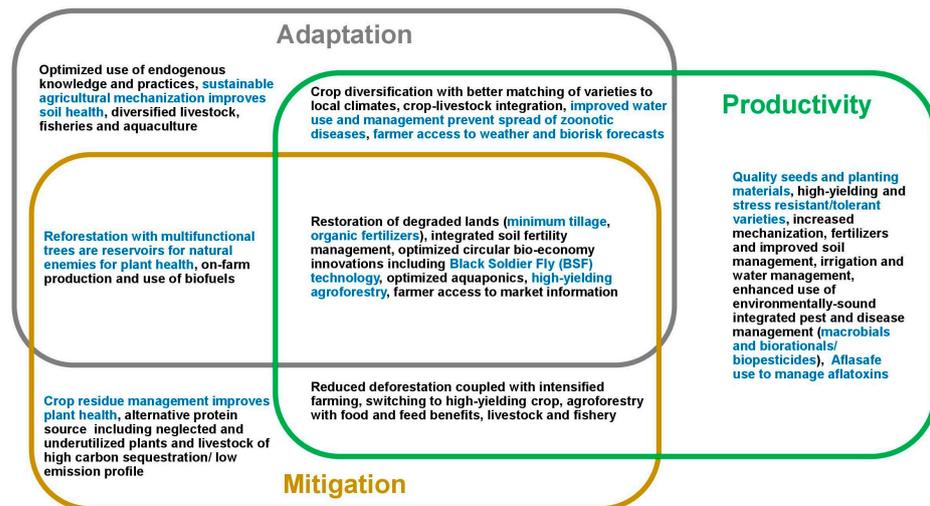
Figure 2. Context-specific intervention framework for Climate-Smart Agriculture (CSA)-led innovations for improved One Health gains [72]. Climate-Smart Agriculture is implemented over three main objectives: (i) improving productivity and (ii) mitigation in food systems, (iii) while building farming communities' resilience. CSA options with specific One Health goals are highlighted in blue font. The same framework can be adjusted to achieve CSA and Climate-Smart Integrated Pest Management (CS-IPM) co-benefits [26].

2.4. Scaling Climate-Smart One Health (CS-OH) Innovations in Ghana

CSA practices/technologies (Figure 2) were prioritized using climate smartness, gender smartness, user-friendliness, and One Health-sensitive indicators. The priority CSAs were disseminated along with Climate Information Services (CIS) in twenty-two (22) communities belonging to six (6) intervention regions of the Accelerating Impacts of CGIAR Climate Research for Africa (AICCRA) project in Ghana (Figure 3).
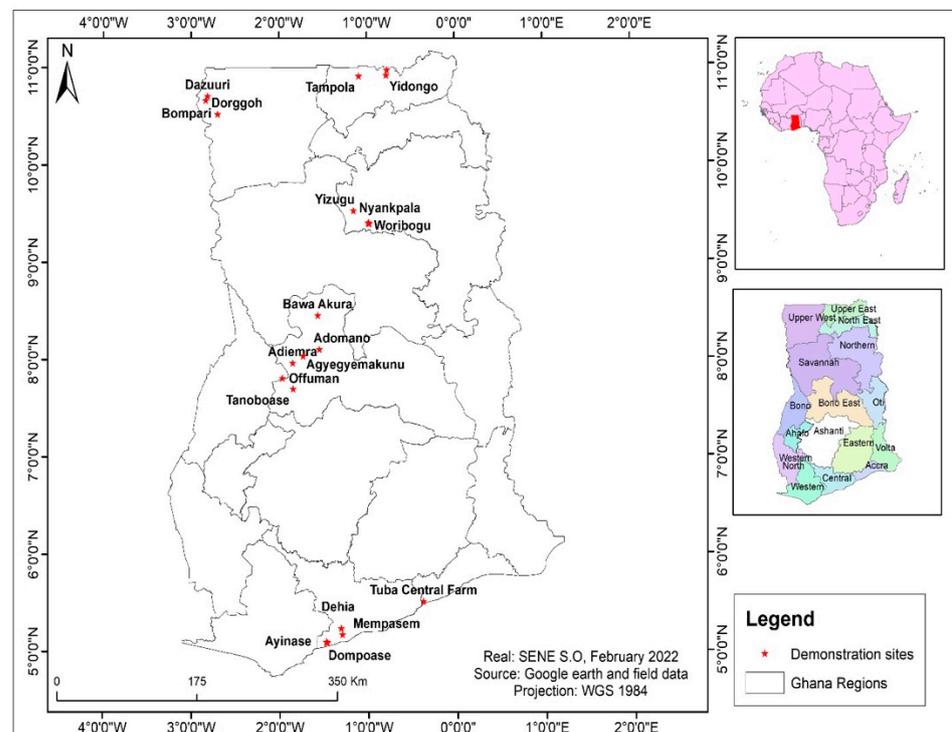

Figure 3. AICCRA project intervention communities with confirmed environmental and social safeguards screening (Map from Serigne Omar Sene, Alliance Bioversity-CIAT).

3. Results

3.1. Achieving Climate Smartness and One Health Targets

Climate-Smart Agriculture is implemented with three main targets: (i) improving productivity and (ii) mitigation outputs in food systems, (iii) while building farming communities' resilience. Therefore, a Climate-Smart One Health (CS-OH) intervention is meant to focus on and promote CSA options with the potential to improve OH outcomes. This action can be strengthened by a range of add-ons including forecasting/prediction of climatic, environmental and biological hazards and information services and/or agronomic advisories.

At its core, OH revolves around interconnectivity. Thus, embodying the spirit of One Health requires focusing on more than a single element or component of the system. To effectively embrace One Health 2.0, it is vital to address a minimum of three elements within the system, such as soil, water, plants, animals and humans, rather than investing solely on animals and humans. Tables 1 and 2 show a set of metrics with interlinked climate smartness and One Health benefits, considering candidate options from Figure 2.

Table 1. Packaging Climate-Smart agricultural options with a view of achieving One Health benefits.

Climate-Smart Agriculture Target	Level of CSA Investment Required *	One Health Gains Likelihood
Productivity	Low	Medium
Mitigation	Low	Low
Adaptation	Low	Low
Productivity–Mitigation	Medium	Medium
Productivity–Adaptation	Medium	High
Mitigation–Adaptation	Medium	Medium
Productivity–Mitigation–Adaptation	High	High

* The table estimates the implementation cost of CSA considering the desired target (productivity, adaptation, mitigation or double- or triple-win CSA) and the associated OH effects/benefits of each investment decision. Single- and double-win CSA targets were weighted considering that achieving the full option of CSA with all objectives targeted together (productivity, adaptation and mitigation) would require deployment of a wide range of technologies and would bear a significant investment cost.

Table 2. Customizing Climate-Smart agricultural packages considering One Health outcome achievement target.

Number of One Health Components Implemented	Associated CSA Investment Requirement	One Health Outcome Achievement Level
Single One Health component *	Low	Nil
Two interconnected One Health components	Medium	Low
Three interconnected One Health components **	Medium to High	Medium to High
More than three interconnected One Health components **	High	High

* One Health components: soil health, water health, plant health, animal health, human health. ** One Health 2.0 highlights high OH outcome chance under full OH implementation option (more than three OH components addressed) and associated CSA investment requirement; the more complex the OH goal/effect desired, the higher the CSA investment needed.

3.2. Ghana: The Champion Country Implementing Climate-Smart One Health

The Ghana Cluster of the Accelerating Impacts of CGIAR Climate Research for Africa (AICCRA: https://aiccra.cgiar.org/, accessed on 5 May 2024) project has taken a proactive role in implementing bundles of Climate-Smart Agriculture (CSA) practices and Climate Information Services (CIS). The selection of CSA practices and technologies was carefully guided by criteria that assessed their climate smartness, gender inclusivity, user-friendliness, and alignment with One Health principles, as detailed in Table 3. These

validated CSA practices and technologies were intentionally chosen to deliver OH benefits across various intervention regions and communities.

Table 3. Pilot list of CSA-CIS options (Figure 2) to achieve One Health outcomes in Ghana.

CSA-CIS Options	Target One Health Response
Use of biorationals (low toxicity pesticides) and biopesticides	Improved plant health Preserved soil–water–animal–human health
Aflasafe (plant bioprotectant against aflatoxins)	Improved plant health (post-harvest) Preserved animal–human health
Minimum tillage	Improved soil health
Organic fertilizers	Improved soil health
Quality vines and seed yam	Improved plant–animal health
Circular bioeconomy-based Black Soldier Fly (BSF) technology (organic waste degradation into organic fertilizers and larval feed for fish and poultry)	Improved plant–soil–water–animal–human health
Farmer-led irrigation	Improved water management/health
Pest-resistant/tolerant varieties	Improved plant–human–animal–ecosystem health
Smart and drought-tolerant varieties	Improved water management Pest and Striga tolerant Preserved soil health
Agroforestry	Improved plant and soil health
Climate and risk information services and advisories	Preserved plant–soil–water–animal–human health

In the year 2022, the collaboration efforts of the AICCRA project have yielded remarkable results, with Climate-Smart Agriculture (CSA) and Climate Information Services (CIS) bundles consisting of packages of CSA practices/technologies and climate information and agronomic advisories, reaching over 260,000 smallholder farmers in six administrative regions and twenty-two communities. The amalgamation of Climate Information Services with Climate-Smart Agriculture technologies has played a pivotal role in enhancing the resilience of farmers' production systems. These strides have been made possible through pilot initiatives conducted within the communities utilizing the validated and bundled CSA and CIS technologies across maize, cowpea, sweet potato and yam value chains. Additionally, outreach efforts, such as farmer field schools and capacity building programs for extension officers and smallholder farmers have further contributed to this progress.

An important aspect to highlight after monitoring and evaluation surveys is that 35% of the beneficiaries of AICCRA's CSA practices and technologies are women and youth, underlining the project's commitment to inclusivity and gender sensitivity. To further advance the dissemination of these validated CSA practices, technologies and climate advisories, a Public–Private–Farmer Partnership (PPFP) approach is considered essential. The success of such a partnership hinges on the value proposition each stakeholder brings to the collective efforts.

In pursuit of effective climate advisories, AICCRA has engaged private sector actors, portrayed by its collaboration with ESOKO, to disseminate climate information, including seasonal and daily forecasts, as well as pest alerts, to smallholder farmers. Participatory technology dissemination approaches such as those promoted by AICCRA, ensure that end-users are actively involved and take ownership of the process, ultimately enhancing the use, adoption and impact of CSA practices and technologies. Furthermore, the acceptance of CSA practices and technologies significantly depends on their accessibility and user-friendliness, aspects that AICCRA has thoughtfully incorporated into its implementation strategy. CS-OH efforts have the potential to transform food systems and ensure sustainability and resilience. However, crucial customized monitoring, evaluation, learning

and impact assessment (MELIA) tools are required to measure the model's efficiency over time and to inform decision-making.

3.3. Designing Climate-Smart Integrated Pest Management (CS-IPM) in Ghana

The communities targeted by the AICCRA project find themselves in the midst of Ghana's climate hotspots, making them particularly susceptible to the adverse impacts of climate change. Additionally, variations in climatic conditions have provided high likelihoods for Invasive Alien Species (IAS) to proliferate and thrive in new environments, as highlighted in Tables 4 and 5 [73]. Recognizing the profound influence of climate variability on pest dynamics and crop productivity, CS-IPM emerges as a crucial component of resilient farming systems. CS-IPM effectively integrates pest management practices with climate adaptation strategies, ensuring that agricultural approaches are not only climate-resilient but also pest-resilient. This approach customizes solutions to local contexts, recognizing that pest and disease challenges can differ significantly across regions. Leveraging scientific advancements, such as climate-informed pest risk assessment models and digital tools, empowers CS-IPM to provide precise, timely and sustainable pest management interventions. Collaborative efforts among stakeholders, knowledge sharing, and the enhancement of ecosystem resilience are fundamental principles that guarantee the effectiveness of CS-IPM. The design of CS-IPM in Ghana entails the creation of a dynamic, adaptive strategy aimed at safeguarding agriculture against climate-driven pest and disease threats, all while promoting sustainability and resilience in the face of an ever-changing climate.

Table 4. Economic impact of key IAS for maize, cassava, and mango in west and central Africa [73].

Host	Invasive Alien Species	Yield Loss Value (Billions, USD)
Maize	*Spodoptera frugiperda*	7.7–12.1
	Prostephanus truncatus	0.2–0.3
	Chilo partellus	2.1–3.1
Cassava	*Phenacoccus manihoti*	5.5–7.3
Mangoes	*Bactrocera dorsalis*	3.5–5.8
Total (billions, USD)		18.2–29.1

Table 5. Economic impact of key IAS in different west and central African countries [73].

Country	Economic Cost (Millions, USD)				
	Spodoptera frugiperda	*Prostephanus truncatus*	*Chilo partellus*	*Phenacoccus manihoti*	*Bactrocera dorsalis*
Burkina Faso	186	-	-	-	2
Cameroon	2237	-	363	79	1
Côte d'Ivoire	211	-	-	495	64
DR Congo	418	-	-	-	451
Ghana	277	14	-	-	94
Nigeria	500	-	-	238	2202
Total (millions USD)	9394	382	2592	6254	5820

3.4. Making a Case for Climate-Smart Integrated Pest Management (CS-IPM)

An illustrative example of early phase detection is the case of the southern armyworm (SAW), scientifically known as *Spodoptera eridania* (Lepidoptera, Noctuidae) [74]. Although this pest was identified in its initial stages of invasion in Africa, it may still pose a significant threat to agriculture in the near future, as depicted in Figures 4 and 5 [75]. Hence, there exists an urgent need to enhance our capabilities for timely threat detection. Doing so

is crucial to prevent the destructive consequences of IAS and to mitigate the overuse of insecticides during outbreaks. A significant hurdle lies in the reluctance of governments and donors to invest in prevention efforts. Advocating for a paradigm shift is becoming increasingly imperative. To effectively make the case for such a shift, robust socioeconomic data must be presented. These data should demonstrate the potential returns on investment in preventive actions against IAS driven by climate, trade and socio-economic developments. Furthermore, it is fundamental to recognize that IPM cannot operate in isolation from the broader scope of climate change. Substantial evidence supports the direct links between climate warning and the proliferation of biorisks, particularly poikilothermic organisms.
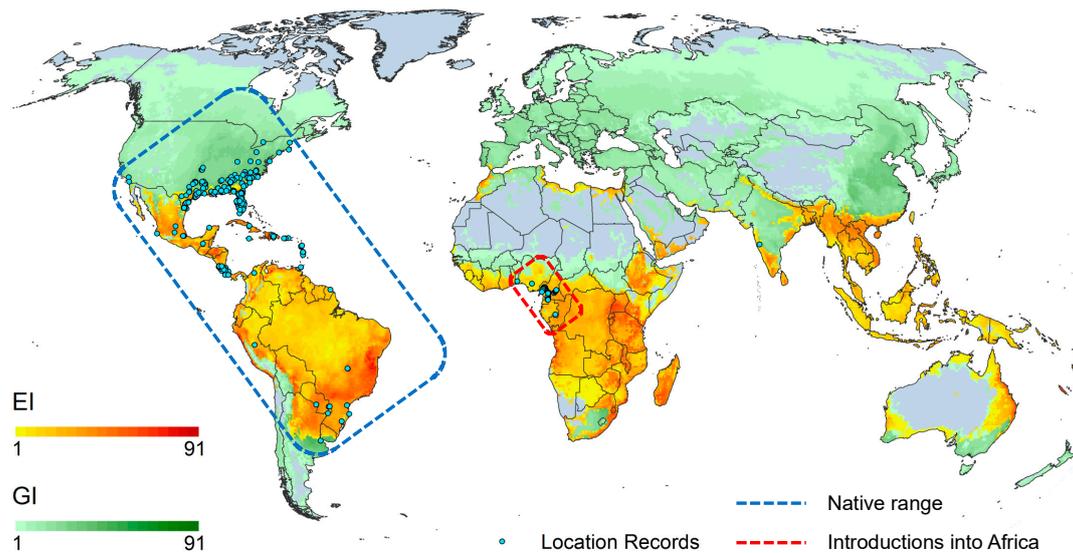

Figure 4. Current global distribution and climatic suitability for *Spodoptera eridania* modeled using CLIMEX. Source of occurrence data: GBIF [75]. EI and GI stand for Ecoclimatic Index and Growth Index, respectively (adapted from Weinberg et al. 2022 [75]).
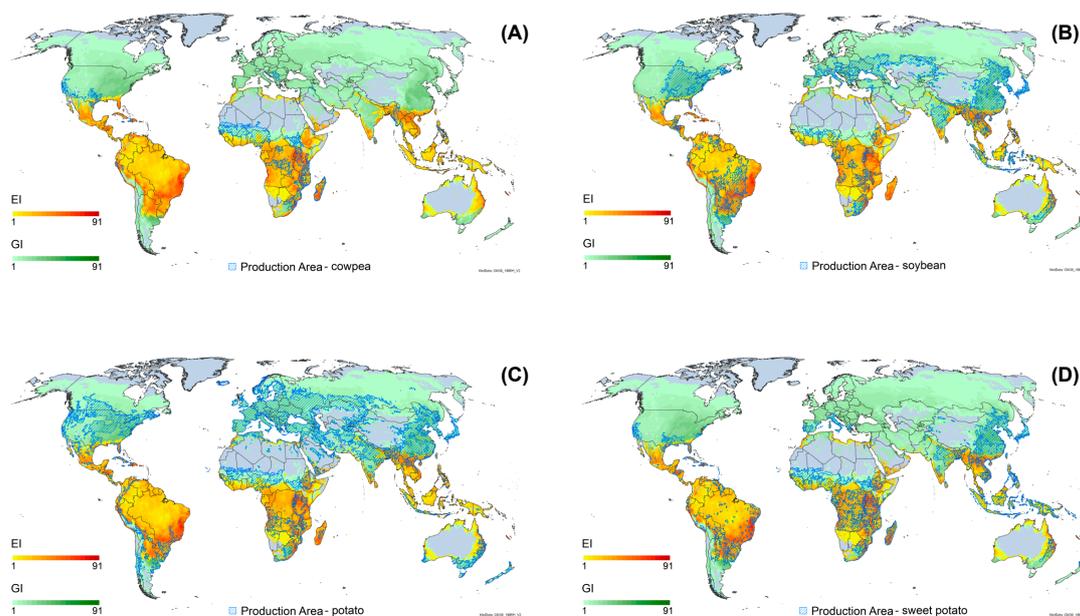

Figure 5. Predictive distribution maps of the southern armyworm (SAW) *Spodoptera eridania*, showing overlaps with a few key crop production areas: cowpea (**A**), soybean (**B**), potato (**C**) and sweet potato (**D**); EI and GI stand for Ecoclimatic Index and Growth Index, respectively (adapted from Weinberg et al. 2022 [75]).

3.5. Climate-Smart Agriculture (CSA) Options with IPM Co-Benefits

An important result from the implementation of AICCRA project is a CS-IPM system, which can be briefly described as achieving IPM benefits within the context of Climate-Smart Agriculture (CSA), as illustrated in Figure 6. CS-IPM serves as the foundational framework through which CSA practices can be effectively disseminated, with a focus on pest management, as depicted in Figure 2. Three pivotal components are essential for the success of CS-IPM, greatly enhancing effectiveness: (i) early warning informed by species distribution modeling under current and future climates, (ii) rapid response and (iii) surveillance and monitoring. These core elements are embodied in the formulated Early Warning and Rapid Response System for Pests and Diseases (EWRRS-PD), a product of the AICCRA project. The comprehensive knowledge process and key drivers required for the successful operationalization of Climate-Smart IPM encompass, but are not restricted to, the following elements [26]:

- Developing climate-informed models for assessing pest risks, identifying potential natural enemies, and enabling forecasting and continuous monitoring. This involves the establishment of technical advisory extension services and harmonized protocols, along with the prioritization of impactful pest management options.
- Ensuring timely detection and proactive measures against invasive species and potential pests exacerbated by climate change.
- Strengthening the capabilities of governmental pest management structures, frontline farmers, and other end-users in effectively reporting, anticipating, and proactively responding to pest- and disease-related challenges.
- Refining and piloting evidence-based innovations and promoting the adoption of digital tools, including Apps-led pest scouting and warning devices.
- Fostering collaboration to establish sustainable business models for pest management services and engaging the private sector to ensure the effective deployment of impactful products and tools. This empowerment initiative should particularly target youth and female farmers.
- Engaging policymakers to create a legislative framework that promotes responsible chemical use and enforces stringent measures against the abusive or unauthorized use of chemicals, especially those that are prohibited and highly toxic to the environment, with significant non-target effects.
- Accelerating the co-development and coordination of functional local and regional early warning and rapid response systems to address pest and disease invasions effectively.

3.6. Early Warning and Rapid Response System for Pests and Diseases (EWRRS-PD)

A generic EWRRS encompasses the following key components: 1. Risk Knowledge—involving public engagement to improve access to risk information through efficient risk communication channels and emergency plans. 2. Monitoring and Warning Services—aimed at enhancing synergies in infrastructure and tools that provide forecasts and warnings related to pests and diseases. Additionally, it advocates for improved legislation and institutional arrangements to promote informal collaboration. 3. Dissemination and Communication—focuses on broadcasting simple and clear warnings using reliable pest and disease forecasts, emphasizing the customization of warning messages through appropriate communication technologies. Advanced strategies are employed to facilitate interactions among primary stakeholders. 4. Response Capability—entails capacity enhancement efforts for increased public and institutional preparedness and for timely and appropriate action by authorities. It advocates for centralized knowledge and emergency plans and the development and application of internal policies, arrangements, procedures and frameworks.
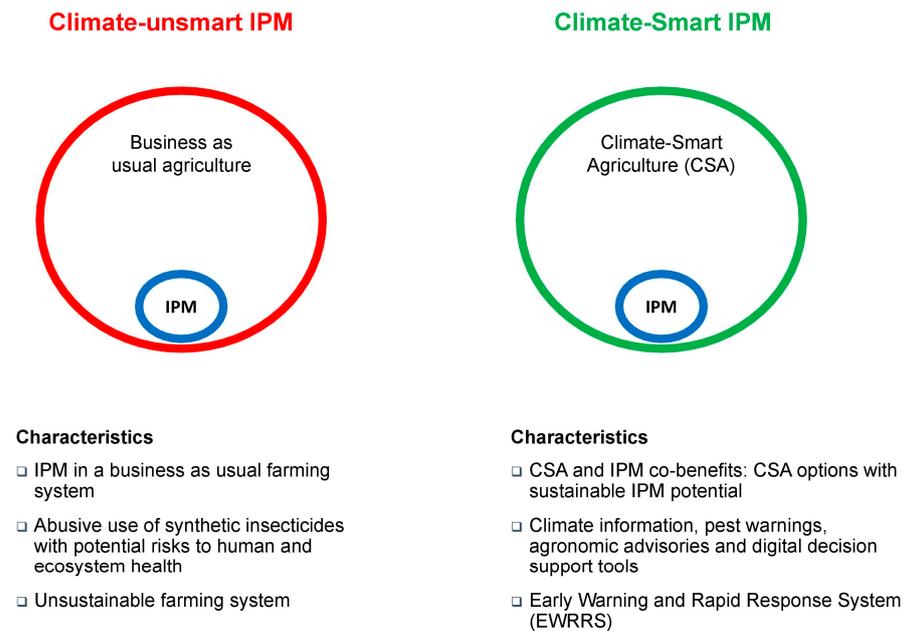
Climate-unsmart IPM　　　　　**Climate-Smart IPM**

Business as usual agriculture

IPM

Climate-Smart Agriculture (CSA)

IPM

Characteristics

❑ IPM in a business as usual farming system

❑ Abusive use of synthetic insecticides with potential risks to human and ecosystem health

❑ Unsustainable farming system

Characteristics

❑ CSA and IPM co-benefits: CSA options with sustainable IPM potential

❑ Climate information, pest warnings, agronomic advisories and digital decision support tools

❑ Early Warning and Rapid Response System (EWRRS)

Figure 6. Climate-unsmart versus Climate-Smart IPM.

3.7. Stakeholder Mapping for Ghana EWRRS-PD

The findings and successful implementations led by the AICCRA project (Ghana Cluster) have played a pivotal role in catalyzing the co-design of an innovative institutional framework known as the Early Warning and Rapid Response System for Pests and Diseases (EWRRS-PD) in Ghana. This groundbreaking tool is underpinned by the Ghanaian Ag-Innovation Data Hub (AIDH), co-developed and hosted at the Institute for Scientific and Technological Information of the Council for Scientific and Industrial Research (CSIR-INSTI). The primary mission of the AIDH revolves around the dissemination of customized climate information, pest and disease alerts, and advisories to key stakeholders and targeted farming communities.

During the AICCRA-led situational analysis in Ghana, farmers voiced their concerns about the emergence of new, climate-induced invasive pests and diseases which pose significant threats to crops such as roots, tubers and vegetables. Without proactive measures, farmers often found themselves unprepared for these emerging threats, resorting to excessive use of insecticides as a reactionary response. This unsustainable practice resulted in adverse consequences, impacting both human and ecosystem health.

The insights assembled from AICCRA's research findings guided the collaborative development of an Early Warning and Rapid Response System for Pests and Diseases (EWRRS-PD) by partners and stakeholders in Ghana. This system is an integral component of the broader Climate-Smart Integrated Pest Management (CS-IPM) strategy. Through consultations with various strategic institutions, it was established that Ghana's Plant Protection and Regulatory Services Directorate (PPRSD) was best suited to lead the co-development of the EWRRS-PD, given its government mandate for pest and disease management in Ghana. To formalize and regulate the EWRRS-PD, a draft memorandum of understanding (MoU) was meticulously crafted and was endorsed and signed by participating organizations, placing it under the stewardship of the PPRSD. The anticipated roles for the different strategic stakeholders involved in this initiative are illustrated in Figure 7. These roles encompass the following:
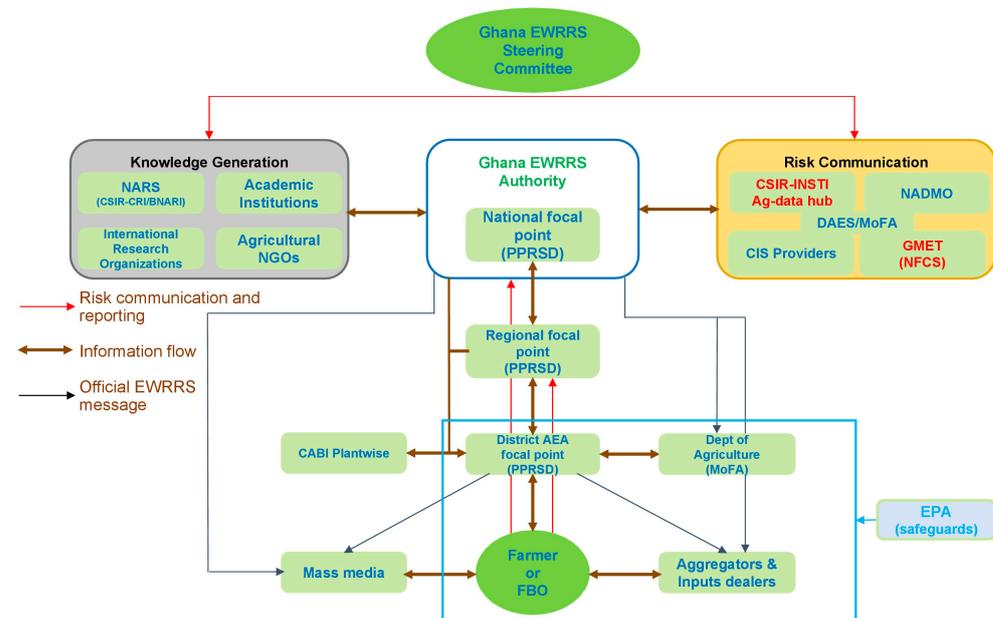
- Reporting

Figure 7. Ghana EWRRS-PD workflow and implementation of support tools. EWRRS-PD: Early Warning and Rapid Response System for Pests and Diseases; NARS: National Agricultural Research System; CSIR-CRI: Council for Scientific and Industrial Research—Crops Research Institute; BNARI: Biotechnologies and Nuclear Atomic Research Institute; NGOs: Non-Governmental Organizations; PPRSD: Plant Protection and Regulatory Services Directorate; CSIR-INSTI: Council for Scientific and Industrial Research—Institute for Scientific and Technological Information; Ag-data hub: Agricultural Innovation Data Hub (AIDH-Ghana); NADMO: National Disaster Management Organization; DAES: Directorate of Agricultural Extension Services; CIS: Climate Information Services; NFCS: National Framework for Climate Services; CABI: Centre for Agriculture and Biosciences International; AEA: Agricultural Extension Agent; MoFA: Ministry of Food and Agriculture; EPA: Environmental Protection Agency; FBO: farmer-based organization.

Selected farmers or farmer-based organizations (FBOs) and Agricultural Extension Agents (AEAs) are tasked with transmitting pest and disease reports (suspected new pest or disease species; serious outbreaks of existing pests and diseases causing havoc) to the Ghana EWRRS-PD Authority (PPRSD).

- Risk knowledge generation

This facet involves the National Agricultural Research System (NARS), academic institutions, international research organizations and agricultural non-governmental organizations (NGOs) engaging in foresight analysis and the generation of pest and disease risk knowledge. In this regard, the CABI Horizon Scanning Tool emerges as a valuable resource.

- Risk mitigation

NARS, academic institutions, international research organizations, and agricultural NGOs are expected to develop and package One Health-compliant IPM products, solutions, technologies and tools aimed at mitigating risks.

- Risk communication

Effective communication is ensured through the efforts of CSIR-INSTI using the Ag-Innovation Data Hub (AIDH), GMET (via the National Framework for Climate Services, NFCS), the National Disaster Management Organization (NADMO) and Climate Information Service (CIS) providers of private companies to transmit risk information to the Ghana EWRRS Authority (PPRSD).

- Monitoring and warning

Selected farmers, agricultural extension agents (AEAs) and the Department of Agriculture at the local government level coordinate routine monitoring and surveillance activities. These encompass methods such as pheromone trapping, field scouting and the utilization of digital tools like pest applications. The Ghana EWRRS Authority (PPRSD) subsequently disseminates pest forecasts and warnings to stakeholders, via various channels including WhatsApp; national, regional and community radio stations; television stations; social media; Climate Information Service (CIS) providers of private companies; and the CSIR-INSTI through the Ag-Innovation Data Hub (AIDH) (AIDH).

- Risk assessment

Institutions equipped with relevant expertise, such as CABI Plantwise and the CSIR—Crops Research Institute—conduct risk assessments and share the outcomes with the Ghana EWRRS Authority (PPRSD).

- Risk and response dissemination

The Ghana EWRRS Authority (PPRSD) disseminates official messages to stakeholders through digital platform outlets of CIS providers; national, regional and community radio stations; television stations; social media; and Farm Radio International (FRI) and related community radios. These messages convey information on the type of risk and relevant response products, solutions, technologies and tools.

- Recycling and capacity strengthening

The Ghana EWRRS Authority (PPRSD), in collaboration with donors and partners, organizes regular recycling and capacity strengthening sessions to enhance the effectiveness of the system. This collaborative effort ensures that the EWRRS-PD remains adaptive and resilient in the face of evolving challenges and dynamics.

4. Discussion

In this endeavor, we have unveiled the complex web of climate change-related challenges that permeate agriculture and food systems, casting a profound shadow over food security, agricultural sustainability and public health [64]. These multifaceted predicaments emerge from the multifarious interplay among climate change, environmental dynamics and biological hazards (agricultural pests and zoonotic diseases), weaving together a complex nexus of concerns, hence necessitating a holistic, interdisciplinary approach to adaptation and mitigation [76]. The evolution of the One Health (OH) concept into what we might call "One Health 2.0" requires a paradigm shift towards system thinking and a deeper recognition of interconnectivity. It goes beyond the traditional focus on zoonotic diseases transmitted between animals and humans. This transformation has elevated the OH framework into a comprehensive, system-oriented approach that recognizes the intricate web of relationships between various components of the environment, particularly in the context of agriculture and food systems. In this more encompassing depiction of OH, we cast a spotlight on linkages that demand examination or consideration from a systemic perspective. Previously overlooked environmental elements, such as soil, water and plant health, now take on greater prominence. These components are not isolated but are integral parts of the larger ecosystem that sustains life on our planet.

One significant addition in this evolved OH framework is the incorporation of climate considerations. Climate change is a defining challenge of our era, and its impacts are felt across all aspects of our lives, including agriculture, food systems and health. Recognizing this, we aim for a more comprehensive and realistic system by integrating climate dynamics into the OH approach. This means consideration of how shifts in temperature, precipitation patterns and extreme weather events not only affect humans and animals but also the health of soils, the quality and availability of water resources and the overall well-being of crops and ecosystems. One Health 2.0 broadens our perspective and encourages to view the world as an intricately interconnected system. It compels us to acknowledge that the health

of humans, animals, plants and the environment is inextricable. By doing so, we gain a more holistic understanding of the challenges we face and can develop more effective and sustainable solutions to address them. This advanced framework reflects the complexity of the world and the need for collaborative, interdisciplinary approaches to safeguard human health and the health of our planet. The current work paves the way for a comprehensive proof of concept in farming communities with OH 2.0-related complex risk models worth exploring in agricultural areas most vulnerable to climate change impacts on the African continent and elsewhere, particularly within the tropical belt from southern America to southeast Asian ecologies. It also unlocks opportunities for the framework adaptation to control and regulate invasive plants and animals.

Climate-Smart Agriculture (CSA) has become increasingly critical in addressing the intricate challenges of climate change adaptation and mitigation and agricultural productivity enhancement. CSA, known for its capacity to deliver triple- and double-wins, addresses economic, social and environmental facets of agricultural sustainability [76]. The triple-win approach of CSA encompasses climate change adaptation, with practices like drought-resistant crop varieties and improved irrigation enhancing resilience to climate variability. It also includes climate change mitigation, with strategies like precision farming reducing emissions and agroforestry sequestering carbon [76]. Furthermore, CSA prioritizes productivity enhancement through sustainable means, promoting higher yields while minimizing environmental impact [76]. To broaden its scope, CSA has been customized into a Climate-Smart OH (CS-OH) model. This innovative adaptation combines CSA principles with a One Health 2.0 approach, acknowledging the interconnections of human, animal, soil, water, plant and ecosystem health within agriculture. This integration allows for a more comprehensive and holistic strategy to address the multifaceted challenges arising from climate change in agriculture and food systems, emphasizing the need to safeguard not only food and nutritional security but also ecosystem integrity and public health [76,77].

Within the framework of CS-OH, a Climate-Smart Integrated Pest Management (CS-IPM) approach is proposed. CS-IPM recognizes the complex relationship between climate dynamics, agricultural practices, and pest and disease outbreaks. It is designed to optimize pest and disease management in a changing climate while minimizing adverse environmental and human and animal health impacts. One of the pivotal components of CS-IPM is the Early Warning and Rapid Response System for Pests and Diseases (EWRRS-PD). This system is crucial in proactively monitoring and predicting the emergence and spread of pests and diseases in response to changing climate conditions. Leveraging data from various sources, including meteorological data, ecological data and risk surveillance, the EWRRS-PD provides timely and accurate information to farmers and relevant stakeholders. When potential threats are detected, the EWRRS-PD triggers rapid response mechanisms, such as targeted interventions, pest control strategies and communication of preventive measures to farmers. The significance of the EWRRS-PD lies in its ability to enhance the resilience of agriculture and food systems. By providing early warnings that facilitate swift responses to pest and disease outbreaks, it helps mitigate crop and livestock losses, reducing economic burdens on farmers and improving food security. Moreover, integrating climate data into its predictions, the EWRRS-PD contributes to climate adaptation by assisting farmers in making informed decisions based on anticipated climate-related challenges.

The CS-OH approach fosters a shared understanding of the complex relationships within agriculture and food systems and promotes innovative solutions that safeguard both environmental integrality and the well-being of communities. In the broader context of CS-OH, the CS-IPM and EWRRS-PD components exemplify the model's holistic and interdisciplinary nature. They underscore the interconnections between climate, agriculture, human health and animal health, emphasizing the need for collaborative efforts among diverse stakeholders, including farmers, researchers, veterinarians, and public health professionals, private sector actors and policymakers. The current CS-OH concept, while providing valuable insights on the interconnections within systems, especially in the context of food systems, has introduced complexity into the veterinary–public health One Health

model. However, the effective implementation of this concept can be a formidable challenge if not meticulously structured and prioritized.

Climate-Smart Agriculture (CSA) was proposed as a candidate two-fold solution to tackle impacts induced by climate change on both agrifood systems and One Health. This may be limiting, particularly in instances when CSA might not sufficiently or accurately address some OH issues like zoonotic diseases' transmission between animals and humans and their management, and therefore requires more insights from veterinary and public health specialists. In addition, only double- and triple-win CSA interventions are predicted to have medium to high OH gains associated with medium to significant CSA investment requirements, which can be a very prominent constraint, especially in most of sub-Saharan African countries. The implementation outline of CS-OH/CS-IPM presented in this work depicts a creative and ambitious tool that addresses and interconnects three major global topics (climate change, food and nutritional security and One Health), requiring extensive multidisciplinary participation that can be only endorsed with existing evidence of high climate adaptation and OH benefits. Finally, the successful realization of CS-OH necessitates careful reviewing of strategic country policies and priorities to facilitate the seamless integration of climate change and food systems to OH endeavors.

Addressing the multifaceted challenges posed by climate change in agriculture and food systems and OH requires a comprehensive strategy. This approach encompasses technological advancements like precision farming, alongside shifts to resilient agricultural practices. It also involves adapting crop and livestock varieties, prioritizing equitable support for vulnerable communities, fostering concerted efforts among various stakeholders, implementing early warning systems for climate- and OH-related risks, promoting data sharing and embracing interdisciplinary collaboration and improved communication. This multilayered strategy aims to mitigate the impacts of climate change on food and nutritional security, agricultural sustainability and public health by addressing the interconnected nature of these challenges and fostering resilience in the face of evolving environmental dynamics. The framework was implemented in Ghana in compliance with the national Public Health and Veterinary Legislation Acts. It also adheres to the Environmental Protection Agency (EPA) Act.

5. Conclusions

We elucidate how climate-induced disruptions, including shifting weather patterns, water scarcity, increased pests and diseases, biodiversity loss and food safety risks, have far-reaching implications for food and nutritional security, agricultural sustainability and public health. Emphasis is placed on the critical interconnections among environmental elements, climate dynamics and biological hazards, highlighting the inadequacy of sector-specific solutions. The current work further advocates for a paradigm shift towards a comprehensive framework, One Health 2.0, which extends beyond zoonotic disease transmission to significantly incorporate a broader array of environmental factors, notably soil, water and plant health. This expanded perspective recognizes the interdependence of these elements within the complex web of agriculture and food systems. To effectively address these multifaceted challenges, the paper underscores the importance of embracing diverse strategies, including technological innovations, sustainable agricultural practices, crop and livestock variety adaptations, and equitable support for vulnerable communities. It also emphasizes the necessity of early warning systems, data sharing and interdisciplinary collaboration and effective communication. In a world where climate change is an ever-escalating concern, this research serves as a clarion call for integrated, cooperative efforts to safeguard food systems and the health of both ecosystems and communities. It is only through such a holistic approach that we can hope to navigate the intricate landscape of climate-induced challenges and build resilience in agricultural and food systems for a more sustainable and secure future. However, it demands substantial investments and rigorous institutional coordination for meaningful and sustainable outcomes. Other measures needed to support the implementation of the framework include subsidies to

mitigate important risks (e.g., soil erosion), saving water resources and reducing the share of waste in agricultural production. The transition to innovative technological processing of organic matter to produce biogas and effective organic fertilizers are also options worth investing. Briefly, this report highlights the following:

- The interconnectedness between soil, water, plants, animals and humans as core elements of a One Health 2.0 model;
- A super ambitious and creative Climate-Smart One Health (CS-OH) framework to address complex climate–OH nexus risks in agrifood systems;
- The basic pillars of Climate-Smart Integrated Pest Management (CS-IPM);
- The investment requirements for both approaches: CS-OH and CS-IPM.

The One Health (OH) 2.0 concept applies to the agricultural sector and more specifically to agrifood systems exposed to climate change impacts. It is meant to address, in a comprehensive manner, soil, water, plant, animal, rural and urban farmers, farming communities, and consumer health issues. OH 2.0 issues with potential to affect three or more of these system elements may involve, but are not limited to, complexes of soil infertility, crop pests and diseases, mycotoxins, pesticide residues, insecticide and antibiotic resistance, crop insect vectors, water-borne infectious diseases, insect vector-borne diseases on animals (e.g., trypanosomiasis) and humans (e.g., malaria, dengue), and other zoonotic and infectious diseases. The One Health (OH) 2.0 concept is embodied in the Climate-Smart One Health (CS-OH) approach. The latter is designed for applications in agrifood systems. The pathways for the deployment of both Climate-Smart One Health (CS-OH) and Climate-Smart Integrated Pest Management (CS-IPM) interventions involve, but are not limited to, the following steps under a bottom-up approach:

- Step 1—OH 2.0 problem characterization, prediction analysis, alerts and demand scope evaluation, government call for action or emergencies to manage OH 2.0 issues.
- Step 2—Mapping of local, national or regional capacity (public and private sectors) on OH 2.0.
- Step 3—Launch of institutional process and stakeholder consultations to agree on lead organization, core strategies, coordination mechanisms, communication tools and channels, and monitoring, evaluation, learning and impact assessment (MELIA) tools, approaches and plans.
- Step 4—Identification of existing and required expertise across the core disciplines of OH 2.0: soil, water and plant health, feed, food and nutritional safety, veterinary and public health, and climate science.
- Step 5—Comprehensive biological- (crop and animal pests and diseases, human infectious or zoonotic diseases), environmental- (hazardous use of pesticides and other agrochemicals) and climate (climate variability and change impacts)-related health risk mapping, assessment and prioritization in target agrifood systems.
- Step 6—Geographic scoping, mapping and prioritization of scalable impactful Climate-Smart Agriculture (CSA) and other relevant solutions to tackle the health risks identified in step 5.
- Step 7—Design of priority OH 2.0 solutions, integrations or bundles and development of dissemination and scaling models.
- Step 8—Baseline survey, solution deployment and monitoring, evaluation, learning and impact assessment (MELIA).

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