frontiers | Research Topics

Climate change, variability and sustainable food systems

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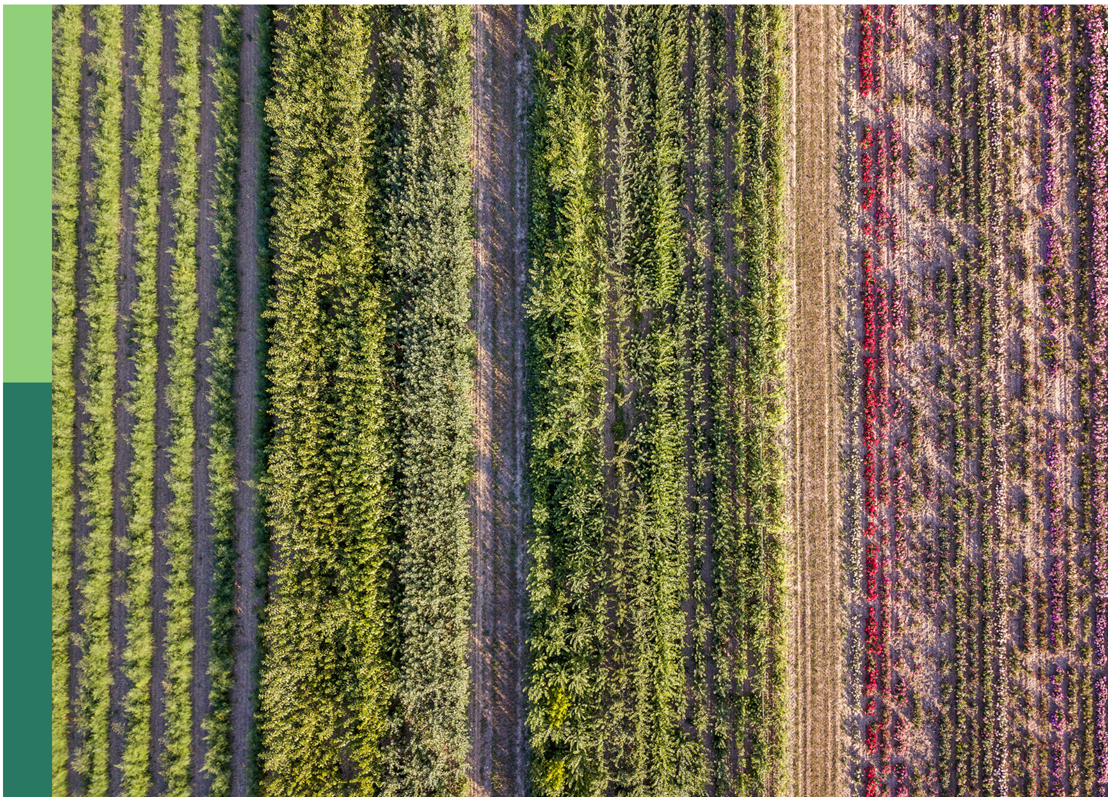
Published in
Frontiers in Sustainable Food Systems



ISSN 1664-8714
ISBN 978-2-83251-481-8
DOI 10.978-2-83251-481-8

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Climate change, variability and sustainable food systems

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Citation
Owusu, V., Asante, B., Donkor, E., Ogundeji, A., Owusu-Sekyere, E., eds. (2023). *Climate change, variability and sustainable food systems*. Lausanne: Frontiers Media SA. doi: 10.3389/978-2-83251-481-8

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frontiers | Frontiers in Sustainable Food Systems

TYPE Editorial
PUBLISHED 13 January 2023
DOI 10.3389/fsufs.2022.912811

OPEN ACCESS

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SPECIALTY SECTION
This article was submitted to Climate-Smart Food Systems, a section of the journal Frontiers in Sustainable Food Systems

RECEIVED 04 April 2022
ACCEPTED 29 December 2022
PUBLISHED 13 January 2023

CITATION
Owusu V, Donkor E, Owusu-Sekyere E, Ogundeji A and Owusu Asante B (2023) Editorial: Climate change, variability and sustainable food systems. *Front. Sustain. Food Syst.* 6:912811. doi: 10.3389/fsufs.2022.912811

Editorial: Climate change, variability and sustainable food systems

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KEYWORDS

climate change, sustainable food systems, climate shocks, developing countries, adaptation strategies

Editorial on the Research Topic
Climate change, variability and sustainable food systems in developing countries

Agri-food systems continue to play a major role in ensuring food security and economic development in many developing countries, particularly Africa and Asia (Tiwari, 2013; FAO, 2021; Norton et al., 2022). In these countries, agrifood systems are the main source of employment for many people at different notes of the chains (Tiwari, 2013). They facilitate industrial development by supplying raw materials, and contribute to curbing malnutrition and food insecurity through provision of nutritious foods (FAO, 2021). Agrifood systems are therefore key pillars to achieving the Sustainable Development Goals (SDG) of No poverty (Goal 1), No hunger (Goal 2), Good health and wellbeing (Goal 3). However, agri-food systems need to be resilient or sustainable enough to supply countries with sufficient and nutritious food to meet the ever-increasing demand under changing climate or climate variability. The greatest challenges confronting the twenty-first-century's food systems in many developing countries are climate change variability and the COVID-19 Pandemic. Notably, smallholder farmers who constitute a major component of agri-food sector in these countries are mostly rainfall-dependent in agricultural production. It is therefore important to build resilient and sustainable food systems by strategically strengthening the adaptive capacities of smallholder producers to sustainably increase farm productivity and food supply. Also, ensuring rural farmers' access and usage of climate information services is crucial in stimulating adaptation measures (Owusu et al., 2021).

In this special issue, we focused on thematic areas that analyzed the nexus between climate change, variability and sustainable food systems in Sub-Saharan Africa and Asia. In total, nine papers were received, including, three review papers and seven original research papers. Three themes that emerged include: (1) the knowledge, perception and impact of carbon-smart technologies, (2) the interaction of health and food systems in changing climate and (3) adaptation strategies to climate change.

Knowledge, perception and impact of carbon-smart technologies

In terms of knowledge and perception, the works by Umar and Horamo et al. evaluated farmers' knowledge and perceptions on the carbon-smart technologies. For instance, using Zambian data, Umar showed that women and men perceived conservation agriculture (CA) to be beneficial in enhancing moisture-holding capacity of basins and increasing crop yields. The study concluded that promotion of adoption of CA package in Zambia should include timely climate information and climate informed crop choices. The study Horamo et al. argued that farmers who accumulate knowledge on tree-crop and tree-animal interactions, on the role of trees in soil fertility, and on crop and livestock improvement, could significantly promote sustainable agriculture. These findings amplify the need to document local knowledge on CA and make them more accessible to development practitioners and other relevant key stakeholders.

From impact viewpoint, adoption of carbon-smart technologies, which are basically farm practices such as tillage reduction, planting of cover crops, using organic fertilizers, agroforestry, crop residue intention and biofuels (FAO, 2021; Yeboah et al.) have the potential to increase the amount of carbon sequestered in the soil. In addition to increasing carbon storage, these practices also improve soil fertility and contribute to sustainable food security by improving crop yields. The study by Yeboah et al. shows that conservation agriculture (CA) and agroforestry technologies tend to increase carbon storage and mitigate the effects of climate change while achieving sustainable food supply to enhance food security. In Ethiopia, Horamo et al. showed that smallholder farmers recorded improved crop yields when they adopted agroforestry as a soil fertility enhancing technology.

Interaction between health and food systems in changing climate

The interactions between food systems and health have also received considerable attention in the academic and policy domains in recent times. Agricultural interventions implemented in the past decades have focused on increasing agricultural productivity, with limited attention paid sustainability and health impacts. For instance, the study by John and Babu reported that the Green Revolution enhanced food security but had unintended negative effects on agriculture and human health in India. They pointed out in the paper that some of the negative health effects include the increasing use of agrochemicals (pesticides and inorganic fertilizers) in agricultural production, which leads to pollution of water bodies, air pollution, imbalance in pest predator and prey as well as extinction of local crop varieties. Using pesticides indiscriminately therefore have dire consequences on human health-related diseases in the nervous, endocrine, reproductive, and immune systems (John and Badu).

Promoting adaptation strategies to climate change

The promotion of climate change adaptation strategies within agri-food system is also gathering momentum in Africa and Asia among policy makers, researchers and development practitioners. For instance, promoting climate-resilient crops such as cassava among smallholder farmers is considered as an agri-food climate change adaptation strategy. A scoping review by Amelework et al. shows that cassava as a climate resilient crop, has the potential for industrial development in South Africa (SA). However, the potential can only be realized if there is reliable supply of quality cassava roots. The study found the lack of a well-established cassava research program and lack of an existing value chain for commercial cassava production as the main barriers to the development of the cassava sector in SA. Also, in India, Ghosh-Jerath et al. revealed that local communities attribute reduced crop yields, reduced diversity and food availability to low and erratic rainfall to long dry spells. Their study contends that declined agroforestry products and diversity could reduce household income and labor migration from agriculture to unskilled wage employment. Also, local communities use adaptation strategies such as climate-resilient indigenous crop varieties for farming, seed conservation and access to indigenous forest foods and weeds for consumption during adverse situations and lean periods to be able to cope with climate variability. The study concludes that promoting sustainable adaptation strategies, with adequate knowledge and technology, could increase farm resilience, income, household food security and dietary diversity. In Bangladesh, Hossain et al. identified high temperatures, cold spells, heavy rainfall and dry spells as key climatic shocks affecting the aquaculture activities, especially pond preparation and maintenance, fingerling stocking, grow-out management, and harvesting sub-sector in the country. The study proposed a decision framework to reduce climate risks and ensure resilience capacity for South Asian aquaculture system. McKinley et al. showed in their study that perceived heat stress, low yield, food insecurity, increased debt, gender (male), education, farm experience, farm size and household size were significant drivers of farmers choice of adaptation strategies to climate change in Vietnam.

Conclusion

In conclusion, sustainable food systems in changing climate should be given a priority by policy makers around the globe, especially in developing countries. This policy agenda could be achieved through the following strategies: First, as indicated in the studies of Yeboah et al. promotion of carbon smart technologies, especially conservation agriculture and agroforestry should be intensified. Secondly, following studies by Umar and Horamo et al., proper documentation of local knowledge on agroforestry practices to them more accessible to development practitioners, thirdly, promotion of climate resilient crop varieties as evidenced in Amelework et al. and Ghosh-Jerath et al.. Fourth, as outlined in Hossain et al., there is the need for development and implementation of appropriate decision framework to reduce climate risk and resilience in aquaculture system and fifth, conducting environmental risk assessment prior to implementation of major agricultural development policies to minimize unintended negative impacts.

Author contributions

All authors listed have made a substantial, direct, and intellectual contribution to the work and approved it for publication.

Acknowledgments

We thank the authors who submitted their papers to this Research Topic. We also appreciate the reviewers for their valuable contributions to improving the quality of the papers submitted.

Conflict of interest

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frontiers in Sustainable Food Systems

MINI REVIEW
published: 22 February 2021
doi: 10.3389/fsufs.2021.644559

Lessons From the Aftermaths of Green Revolution on Food System and Health

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Food production has seen various advancements globally in developing countries, such as India. One such advancement was the green revolution. Notably, the World Bank applauds the introduction of the green revolution as it reduced the rural poverty in India for a certain time. Despite the success of the green revolution, the World Bank reported that health outcomes have not been improved. During the post-green revolution period, several notable negative impacts arose. Exclusive studies were not conducted on the benefits and harms before the introduction of the green revolution. Some of such interventions deviate from the natural laws of balance and functioning and are unsustainable practices. To avoid the adverse effects of some of these developments, a review of these interventions is necessary.

Keywords: green revolution, sustainability, food system, agriculture, India

OPEN ACCESS

Edited by:
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Specialty section:
This article was submitted to Climate-Smart Food Systems, a section of the journal Frontiers in Sustainable Food Systems

Received: *21 December 2020*
Accepted: *13 January 2021*
Published: *22 February 2021*

Citation:
John DA and Babu GR (2021) Lessons From the Aftermaths of Green Revolution on Food System and Health. Front. Sustain. Food Syst. 5:644559. doi: 10.3389/fsufs.2021.644559

INTRODUCTION

The production of food within India was insufficient in the years from 1947 to 1960 as there was a growing population, during which a famine was also anticipated (Nelson et al., 2019). Food availability was only 417 g per day per person (Ghosh, 2002). Many farmers were in debt, and they had become landless laborers. Political situations that prevailed also had a negative impact on the food system. There was a severe shortage of food crops as well as commercial crops. At the same time, Norman Borlaug, an agronomist, contributed to the green revolution significantly, and this had set out its effects throughout the world. He provided new seeds for cultivation, which were stocky, disease-resistant, fast-growing, and highly responsive to fertilizers. In India, the green revolution was launched under the guidance of geneticist Dr. M. S. Swaminathan (Somvanshi et al., 2020). It started around 1960s and helped in increasing food production in the country. The green revolution's primary aim was to introduce high-yielding varieties (HYVs) of cereals to alleviate poverty and malnutrition (Nelson et al., 2019). Not to deny, the green revolution was capable of mitigating hunger and malnutrition in the short term as well (Davis et al., 2019).

What Is the Green Revolution?

The green revolution led to high productivity of crops through adapted measures, such as (1) increased area under farming, (2) double-cropping, which includes planting two crops rather than one, annually, (3) adoption of HYV of seeds, (4) highly increased use of inorganic fertilizers and pesticides, (5) improved irrigation facilities, and (6) improved farm implements and crop protection measures (Singh, 2000; Brainerd and Menon, 2014) and modifications in farm equipment. There was a high investment in crop research, infrastructure, market development, and appropriate policy support (Pingali, 2012). Efforts were made to improve the genetic component of traditional crops. This included selection for higher yield potential; wide adaptation to diverse environments; short growth duration; superior grain quality; resistance to biotic stress, insects, and pests; and resistance to abiotic stress, including drought and flooding (Khush, 2001). After the green revolution, the production of cereal crops tripled with only a 30% increase in the land area cultivated. This came true all over the world, with a few exceptions. In addition, there were significant impacts on poverty reduction and lower food prices. Studies also showed that without the green revolution, caloric availability would have declined by around 11–13%. These efforts benefitted all consumers in the world, particularly the poor. There were further improved returns to the crop improvement research. It also prevented the conversion of thousands of hectares of land for agriculture (Pingali, 2012). The green revolution helped India move from a state of importing grains to a state of self-sufficiency (Brainerd and Menon, 2014). Earlier, it was the ship-to-mouth system, i.e., India depended on imported food items (Ramachandran and Kalaivani, 2018). There are undoubtedly positive effects on the overall food security in India. Correspondingly, useful and elaborate evidence in support of the positive impact of the green revolution is available. However, after a certain period, some unintended but adverse effects of the green revolution were noticed. This paper introspects the negative impacts of the green revolution on the food system in India. Studies by the departments of conventional agriculture, social sector development, etc. bring out the positive impacts of the green revolution, such as increased yield and reduced mortality and malnutrition (Somvanshi et al., 2020; von der Goltz et al., 2020). On the other hand, studies conducted by the environmental and public health departments suggest that to mitigate the negative impacts, a reduced usage of pesticides is sufficient (Gerage et al., 2017). There are many studies being conducted to find out the extent of the impacts of pesticides and insecticides and other similar chemicals.

Although there are many studies that focused on this topic, this paper makes an effort to inform policy by asserting that many interventions, beneficial for the shorter term, such as the green revolution, without the consideration of ecological principles, can be detrimental and irreversible in the long run (Clasen et al., 2019). Efforts to recover from environmental damage would require extensive efforts, time, and other resources as compared with the destruction of the environment. Hence, any new intervention needs to be checked for its eco-friendliness and sustainability features.

Carrying forward intensified usage of pesticides is not advisable in an ever-deteriorating environment, and alternative solutions that can promote economic growth, increased yield, and less harm to the environment can be implemented. The vicious cycle of problem-solution-negative impacts has to be broken at some point of time. For example, a second green revolution is focused on in various countries (Ameen and Raza, 2017; Armanda et al., 2019). Instead of this, techniques to promote sustainable agriculture can be considered. Hence, there has to be a wake-up call before the repetition of history.

Impacts of the Green Revolution

Impacts on Agriculture and Environment

Pests and Pesticide

There has been a significant increase in the usage of pesticides, and India became one of the largest producers of pesticides in the whole of Asia (Narayanan et al., 2016). Although this has contributed to a lot of economic gains (Gollin et al., 2018), it is found out that a significant amount of pesticides is unnecessary in both industrialized and developing countries. For instance, it is reported that the presence of pesticides within freshwater is a costly concern with detected levels exceeding the set limits of pesticide presence (Choudhary et al., 2018). Although the average amount of pesticide usage is far lower than in many other countries, there is high pesticide residue in India. This causes a large amount of water pollution and damage to the soil. Another major issue is the pest attack, which arises due to an imbalance in the pests. Due to increased pesticide usage, the predator and prey pests are not in balance, and hence there is an overpopulation of one kind of pest that would attack certain crops. This leads to an imbalance in the production of those kinds of crops. These crops would need stronger pesticides or pesticides of new kinds to tackle the pests attacking those. This also has led to the disruption in the food chain (Narayanan et al., 2016).

Water Consumption

India has the highest demand for freshwater usage globally, and 91% of water is used in the agricultural sector now (Kayatz et al., 2019). Currently, many parts of India are experiencing water stress due to irrigated agriculture (Davis et al., 2018). The crops introduced during the green revolution were water-intensive crops. Most of these crops are cereals, and almost 50% of dietary water footprint is constituted by cereals in India (Kayatz et al., 2019). Since the crop cycle is less, the net water consumed by these crops is also really high. The production of rice currently needs flooding of water for its growth[1] (International Rice Research Institute). Canal systems were introduced, and there were irrigation pumps that sucked out water from the groundwater table to supply the water-intensive crops, such as sugarcane and rice (Taylor, 2019). Punjab is a major wheat- and rice-cultivating area, and hence it is one of the highest water depleted regions in India[2] (Alisjahbana, 2020). It is predicted that Punjab will have water scarcity in a few years (Kumar et al., 2018). Diminishing water resources and soil toxicity increased the pollution of underground water. The only aim of the green revolution was to increase food items' production and make it sufficient to feed everyone. The environmental impacts were not taken into account (Taylor, 2019). Based on the previous allocation of budget, irrigation was allotted 9,828 crore INR as compared with 3,080 crore INR for agriculture, excluding irrigation. This pattern has been persistent in the past 3 years (NABARD, 2020). Overall, the GDP from agriculture is 380,239 crore INR (16.5% of GDP) (Economics, 2020; India, 2020). This

[1]http://www.knowledgebank.irri.org/step-by-step-production/growth/water-management

[2]https://www.unescap.org/op-ed/asia-pacific-response-covid-19-and-climate-emergency-must-build-resilient-and-sustainable

indicates that there has been a higher investment on irrigation of water due to its increased need in comparison with the other inputs required for agriculture.

Air Pollution

Air pollution introduced due to the burning of agricultural waste is a big issue these days. In the heartland of the green revolution, Punjab, farmers are burning their land for sowing the crops for the next cycle instead of the traditionally practiced natural cycle. The next crop cycle arrives very soon because the crop cycle is of short duration for the hybrid crops introduced in the green revolution. This contributes to the high amount of pollution due to the burning of agricultural waste in parts of Punjab (Davis et al., 2018). This kind of cultivation can lead to the release of many greenhouse gases, such as carbon dioxide, methane, nitrogen oxides, etc. (de Miranda et al., 2015).

Impacts on Soil and Crop Production

There was a repetition of the crop cycle for increased crop production and reduced crop failure, which depleted the soil's nutrients (Srivastava et al., 2020). Similarly, as there is no return of crop residues and organic matter to the soil, intensive cropping systems resulted in the loss of soil organic matter (Singh and Benbi, 2016). To meet the needs of new kinds of seeds, farmers used increasing fertilizers as and when the soil quality deteriorated (Chhabra, 2020). The application of pesticides and fertilizers led to an increase in the level of heavy metals, especially Cd (cadmium), Pb (lead), and As (arsenic), in the soil. Weedicides and herbicides also harm the environment. The soil pH increased after the green revolution due to the usage of these alkaline chemicals (Sharma and Singhvi, 2017). The practice of monoculture (only wheat–rice cultivation) has a deleterious effect on many soil properties, which includes migration of silt from the surface to subsurface layers and a decrease in organic carbon content (Singh and Benbi, 2016). Toxic chemicals in the soil destroyed beneficial pathogens, which are essential for maintaining soil fertility. There is a decrease in the yield due to a decline in the fertility of the soil. In addition, the usage of tractors and mechanization damaged the physicochemical properties of the soil, which affected the biological activities in the soil. In the traditional methods, soil recovers in the presence of any kind of stressors (Srivastava et al., 2020). However, this does not happen with these modern methods. In a study conducted in Haryana, soil was found to have waterlogging, salinity, soil erosion, decline, and rise of groundwater table linked to brackish water and alkalinity, affecting production and food security in the future (Singh, 2000).

Although for around 30 years there was an increase in the production of crops, the rice yield became stagnant and further dropped to 1.13% in the period from 1995 to 1996 (Jain, 2018). Similarly with wheat, production declined from the 1950s due to the decrease in its genetic potential and monoculture cropping pattern (Handral et al., 2017). The productivity of potato, cotton, and sugarcane also became stagnant (Singh, 2008). Globally, agriculture is on an unsustainable track and has a high ecological footprint now (Prasad, 2016).

Extinction of Indigenous Varieties of Crops

Due to the green revolution, India lost almost 1 lakh varieties of indigenous rice (Prasad, 2016).

Since the time of the green revolution, there was reduced cultivation of indigenous varieties of rice, millets, lentils, etc. In turn, there was increased harvest of hybrid crops, which would grow faster (Taylor, 2019). This is indicated in **Figure 1**. There is a large increase in the cultivation of wheat, soybeans, and rice. In addition, there is a large decrease in the cultivation of sorghum, other millets, barley, and groundnuts. The increase in certain crops was due to the availability of HYVs of seeds and an increase in the area of production of these crops (Singh, 2019). The preference of farmers also changed in terms of the cultivation of crops. The native pulses, such as moong, gram, tur, etc., and some other oilseed crops, such as mustard, sesame, etc., were not cultivated further on a larger scale than it was before. Traditionally grown and consumed crops, such as millets, grow easily in arid and semi-arid conditions because they have low water requirements. However, there was the unavailability of high-yielding seeds of millets, and hence farmers moved to only rice and wheat (Srivastava et al., 2020).

Impacts on Human Health

Food Consumption Pattern

Traditionally, Indians consumed a lot of millets, but this became mostly fodder after the green revolution (Nelson et al., 2019). The Cambridge world history of food mentions that the Asian diet had food items, such as millets and barley (Kiple and Ornelas, 2000). As already mentioned, after the period of the green revolution, there were significant changes in food production, which in turn affected the consumption practices of Indians. The Food and Agriculture Organization (FAO) has recorded that over the years 1961–2017, there are a decrease in the production of millets and an increase in the production of rice (Food and Agricultural Organisation, 2019; Smith et al., 2019); thus, rice became the staple diet of the country. Though the green revolution made food available to many, it failed to provide a diverse diet but provided increased calorie consumption.

Health-Related Impacts on the General Population

Most of the pesticides used belong to the class organophosphate, organochlorine, carbamate, and pyrethroid. Indiscriminate pesticide usage has led to several health effects in human beings in the nervous, endocrine, reproductive, and immune systems. Sometimes, the amount of pesticide in the human body increases beyond the capacity of the detoxification system due to continuous exposure through various sources (Xavier et al., 2004). Of all, the intake of food items with pesticide content is found to have high exposure, i.e., 10^3-10^5 times higher than that arising from contaminated drinking water or air (Sharma and Singhvi, 2017).

Impacts on Farmers

Most of the farmers who use pesticides do not use personal protective gear, such as safety masks, gloves, etc., as there is no awareness about the deleterious effects of pesticides. Pesticides, applied over the plants, can directly enter the human body,

Crops	1961	2018
Wheat	12,927K	29,580K
Soybeans	11K	11,400K
Rice, paddy	34,694K	44,500K
Beans, dry	6,541K	13,546K
Maize	4,507K	9,200K
Seed cotton	7,719K	12,350K
Pigeon peas	2,433K	5,583K
Chick peas	9,276K	11,899K
Sugar cane	2,413K	4,730K
Jute	917K	764K
Peas, dry	1,177K	998K
Oilseeds nes	477K	201K
Safflower seed	440K	103K
Sesame seed	2,252K	1,730K
Pulses nes	3,592K	2,210K
Linseed	1,789K	320K
Groundnuts, with shell	6,889K	4,940K
Barley	3,205K	661K
Millet	18,657K	9,107K
Sorghum	18,249K	4,960K

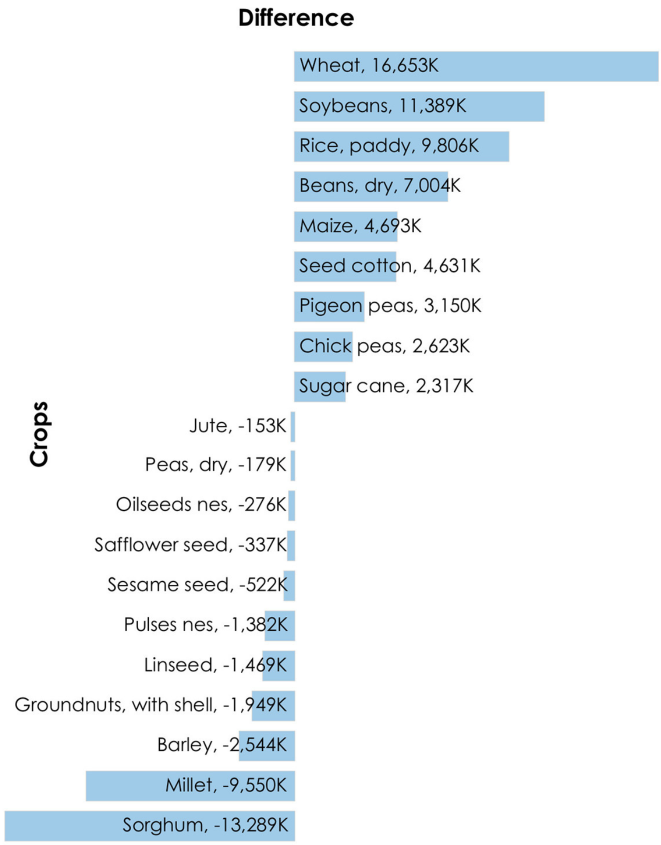

FIGURE 1 | Changes in area harvested of the crops from the years 1961 to 2018 (data source: FAOSTAT; FAO, 2020).

and the concentration of nitrate in the blood can immobilize hemoglobin in the blood. Organophosphates can also develop cancer if exposed for a longer period. Since it is in small quantities, the content may not be seen or tasted; however, continuous use for several years will cause deposition in the body. Dichlorodiphenyltrichloroethane (DDT) was a very common pesticide used in India, now banned internationally as it is found to bioaccumulate and cause severe harmful effects on human beings (Sharma and Singhvi, 2017). However, there is still illegal use of DDT in India. In India, women are at the forefront of around 50% of the agricultural force. Hence, most of these women are directly exposed to these toxins at a young age and are highly vulnerable to the negative impacts including effects on their children. It is proven that there is a significant correlation between agrochemical content in water and total birth defects. The damaging impact of agrochemicals in water is more pronounced in poor countries, such as India (Brainerd and Menon, 2014).

DISCUSSION

Efforts are underway to produce genetic variants of millets that can withstand biotic and abiotic stresses. Earlier, the introduction of genetic variants of rice and wheat and pesticides was the solution for malnutrition, but it led to environmental destruction in a few years. In the short term, food scarcity might rise again due to increased water depletion and soil damage. Any new interventions should be carefully introduced not to disrupt other systems to prevent future adversities. A domino effect is expected to occur when there is any disruption in the ecosystem, such that if even one link in the food chain is affected, it affects other parts of the chain also. Most of the ecological disruption is by human intervention (Vaz et al., 2005). Pesticides used for agricultural activities are released to the environment through air drift, leaching, and run-off and are found in soil, surface, and groundwater. This can contaminate soil, water, and other vegetation. Pesticide residues are found to be present in almost all habitats and are detected in both marine and terrestrial animals (Choudhary et al., 2018). The mechanisms include absorption through the gills or teguments, which is bioconcentration, as well as through the consumption of contaminated food, called biomagnification or bioamplification. In marine systems, seagrass beds and coral reefs were found to have very high concentrations of persistent organic pollutants (Dromard et al., 2018). It also affects the activities of insects and microbes. It kills insects and weeds, is toxic to other organisms, such as birds and fish, and contaminates meat products, such as chicken, goat, and beef. This can lead to bioaccumulation in human beings along with poor food safety, thus impairing nutrition and health. Repeated application leads to loss of biodiversity (Choudhary et al., 2018). Consumption of pesticide-laden food can lead to loss of appetite, vomiting, weakness, abdominal cramps, etc. (Gerage et al., 2017). There is a decline in the number of pollinators, for instance, the destruction of bumblebee colonies that are an important group of pollinators on a global scale (Baron et al., 2017). There is an extinction of honeybee populations, and it poses a great threat to the survival of human beings (Hagopian, 2017). The residue level of these pesticides depends on the organism's habitat and position in the food chain. This is a serious issue because the predicted usage of pesticides is that it will be doubled in the coming years (Choudhary et al., 2018).

In addition, it is not nearly possible to get back the lost varieties of indigenous rice. Likewise, further advancements should not lead to the extinction of the other indigenous varieties of grains, such as millets.

In conclusion, the effects of the green revolution are persisting. The green revolution, which was beneficial in ensuring food security, has unintended but harmful consequences on agriculture and human health. This requires new interventions to be tested and piloted before implementation, and continuous evaluation of the harms and benefits should guide the implementation. An already fragile food system is affected due to the aftermaths of the green revolution. The potential negative impacts are not part of the discourse as it can affect the narratives of development and prosperity. Developments introduced due to necessity may not be sustainable in the future. Organic ways of farming need to be adopted for sustainable agricultural practices. Similarly, alternative agriculture techniques, such as intercropping, Zero Budget Natural Farming (ZBNF) with essential principles involving the enhancement of nature's processes, and elimination of external inputs, can be practiced (Khadse et al., 2018). The government of Andhra Pradesh (AP), a Southern state in India, has plans to convert 6 million farmers and 8 million hectares of land under the state initiative of Climate Resilient Zero Budget Natural Farming because of the positive outputs obtained in the ZBNF impact assessments in the states of Karnataka and AP (Reddy et al., 2019; Koner and Laha, 2020) In AP, it was observed that yield of crops increased to 9% in the case of paddy and 40% in the case of ragi. Net income increased from 25% in the case of ragi ranging to 135% in the case of groundnut (Martin-Guay et al., 2018; Reddy et al., 2019). There is a need for a systems approach in dealing with food insecurity and malnutrition and other similar issues. Like the already mentioned example, the green revolution was brought in to reduce the problem of reduced yield. Now, there is a green revolution 2 that is planned. Before such interventions are taken, environmental risk assessments and other evaluation studies should be conducted for a sustainable future.

AUTHOR CONTRIBUTIONS

DJ conceived the idea. DJ and GB contributed to the writing of the article. Both the authors contributed to the review, proofreading, and finalizing the manuscript.

FUNDING

This MAASTHI cohort was funded by an Intermediate Fellowship by the Wellcome Trust DBT India Alliance (Clinical and Public Health research fellowship) to GB (grant number IA/CPHI/14/1/501499). The funding agency had no role in the design and conduct of the article, review and interpretation of the data, preparation or approval of the manuscript, or decision to submit the manuscript for publication.

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Conflict of Interest: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

frontiers in Sustainable Food Systems

REVIEW
published: 15 April 2021
doi: 10.3389/fsufs.2021.617783

Adoption and Promotion of Resilient Crops for Climate Risk Mitigation and Import Substitution: A Case Analysis of Cassava for South African Agriculture

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Specialty section:
This article was submitted to Climate-Smart Food Systems, a section of the journal Frontiers in Sustainable Food Systems

Received: 15 October 2020
Accepted: 17 March 2021
Published: 15 April 2021

Citation:
Amelework AB, Bairu MW, Maema O, Venter SL and Laing M (2021) Adoption and Promotion of Resilient Crops for Climate Risk Mitigation and Import Substitution: A Case Analysis of Cassava for South African Agriculture. Front. Sustain. Food Syst. 5:617783. doi: 10.3389/fsufs.2021.617783

Cassava is an important starchy root crop grown globally in tropical and subtropical regions. The ability of cassava to withstand difficult growing conditions and long-term storability underground makes it a resilient crop, contributing to food security. Historically, small-scale farmers have grown cassava as a minor crop in the far north-eastern part of the country. However, there is an initiative to scale up cassava production, with two discrete areas of interest: large-scale production for industrial starch, and expanding its footprint as a food security crop for small-scale farmers, especially in the context of climate change. In this scoping study, production, processing and marketing data for cassava were accessed from the FAO and US Commercial trade databases. Other domestic market and demand analysis case studies were also explored. There is no cassava data available for South Africa. The study indicated that South Africa imports more than 66,000 tons of starch annually, of which 33% is cassava starch, showing the availability of a local market. The potential of cassava for the South African economy is discussed. Significant industrial opportunities exist for the production and use of cassava in South Africa. However, the realization of these opportunities will depend on the reliable supply of good quality cassava roots. However, the lack of a well-established cassava research program, and a lack of an existing value chain for the industrial scale cassava production and processing are barriers to the development of cassava industry in South Africa. As the initial step to the development of a successful cassava industry, high potential germplasm is imported, characterized and bred for local conditions to ensure the sustainable primary production of cassava. Subsequently, industrial value chains will need to be developed as the optimization of the breeding and agronomy of the crop are completed, and yield potentials are quantified in the different regions of the country.

Keywords: cassava breeding, climate change, import substitute, industrial application, value chain

INTRODUCTION

Southern African Development Community (SADC) has recognized cassava as one of the potential industrial crops for SADC farmers (SADC Trade information Service). Cassava plays a key role in rural livelihoods in Africa especially in the tropics where the environment is both hot and dry. However, cassava is not among the traditional commodity crop in South Africa. South Africa's interest in cassava cultivation is mainly on high quality industrial starch production. Conversely, cassava is a versatile crop that offers immense opportunity as a food, feed, and industrial crop. In South Africa, the most suitable areas for cassava production are northern KwaZulu-Natal, the eastern parts of Limpopo and Mpumalanga. These areas all together have two million hectares of arable land, which is below 800 m elevation and an annual rainfall of 500 mm that is suitable for cassava production. However, currently smallholders in the far north-eastern region in South Africa have grown cassava as a minor crop.

The National Industrial Policy facilitates crop diversification beyond the country's current reliance on traditional crop commodities to promote non-traditional commodities that compete in export markets and reduce imports. This opens windows to promote cassava production in South Africa. Moreover, water scarcity presents difficulty in cropping maize, wheat and potato. Cassava has the ability to grow in a wider range of climatic conditions and soil types than other tropical staple crops. Relative to grain crops, cassava is more tolerant of low soil fertility and is more resistant to drought. Hence, cassava can provide South Africa with options for adaptation, whilst other major staples crops like maize and wheat face challenges. In addition, cassava has the potential to produce and store more carbohydrate than any other major grain or root crops (El-Sharkawy and De Tafur, 2010). It can provides an option for the development of a novel industrial crop, with more than 300 industrial products including the manufacture of tire, adhesives, ethanol, pharmaceuticals, livestock feeds, biofuels, cold meats, and alcohol.

Characteristics such as low input requirements, tolerance to drought, the ability to grow in marginal soils and long-term storability of the roots in the ground make cassava a resilient crop for food and nutritional security (Jarvis et al., 2012). Cassava roots can be stored underground for as long as 24 months after maturity, and these can be harvested at any time of the year when a household needs food (Sanchez et al., 2013). Farmers can plant and harvest cassava without significant inputs, using marginal lands where other crops cannot be produced. Cassava typically yields 8–10 tons ha-1 of fresh storage roots with zero inputs. Consequently, cassava is widely produced in tropical regions by small-scale resource-limited farmers, who cannot afford to buy agro-chemicals or install irrigation systems (Costa and Delgado, 2019). Cassava provides an opportunity to improve smallholder farmers' income and food security by opening up marginal lands for cultivation.

Despite cassava's importance as a food security crop in Africa, and its industrial potential, relatively little research and development has been invested in cassava in southern Africa, compared to other root crops such as potato and sweet potato. There was a commercial starch processing plant that ran for several years in Mpumalanga but it has ceased to operate due to lack of raw material supply. Because, cassava production is dominated by disease-prone varieties with long maturation periods and low yield potential. Designing of a well-coordinated and well-structured cassava breeding program in the country is essential to create improved cassava cultivars with enhanced tuber yields and starch content as the basis for a cassava industry in South Africa. The increase in yield will lead to an increase in raw material supply to the industrial sector, which, in turn, will lead to an increase in income for the resource-poor farmers. In this desktop study, the importance of cassava as food, feed, and industrial crop has been reviewed. The study deals with the potential of cassava in the South African starch industry, the significance of crafting a sustainable R&D strategy to support the industry, the development of the full value chain, and the importance of a national cassava breeding program. It is envisaged that this document will serve as a guide to develop the right technologies and appropriate approaches for integrating cassava into the farming system and to deliver economic benefits to both commercial and smallholder farmers.

CASSAVA PRODUCTION IN THE WORLD

The total worldwide cassava production in 1961 was 78.5 million tons grown on 9.6 million hectares, of which Africa contributed about 44% (FAOSTAT, 2019). By 2017, world cassava production had increased to 322 million tons grown on 26 million ha of land (FAOSTAT, 2019). Although Africa accounts for more than 58% of cassava production and more than 75% of land area cultivated for cassava, the average fresh root yield of cassava is 8.9 t ha^{-1}, which is far lower than the world average (11.9 t ha^{-1}) and the yield observed in Asia (13.3 t ha^{-1}) (FAOSTAT, 2019). Cassava is grown in more than 105 counties; Nigeria, Democratic Republic of the Congo, Brazil, and Indonesia are the leading cassava producers. Cassava fresh root yields under smallholder farmer conditions have been estimated about 1–10 t ha^{-1}. However, fresh root yields can potentially reach 75–80 t ha^{-1} through the use of high yielding, best adapted cultivars and improved crop management practices (Anikwe and Ikenganyia, 2017).

Cassava production has shown a steady growth for the last six decades. The most dramatic increase in Africa and Asia were observed from 1996 to 2017 (**Figure 1A**). Cassava production in Latin America, on the other hand, showed more moderate increases. The large increase in cassava production can be attributed partly to an increase in area harvested in Africa as farmers recognize the economic importance of the crop (**Figure 1B**) and partly due to a substantial yield gains in Asia due to new improved cultivars and improved agronomic practices (**Figure 1C**) (Aye and Howeler, 2017). Cassava production and the demand for cassava are expected to grow largely because of the crop's ability to withstand drought and provide reasonable yields on marginal and low-fertility soils. Many countries have realized the economic potential of the crop as a food, feed, and

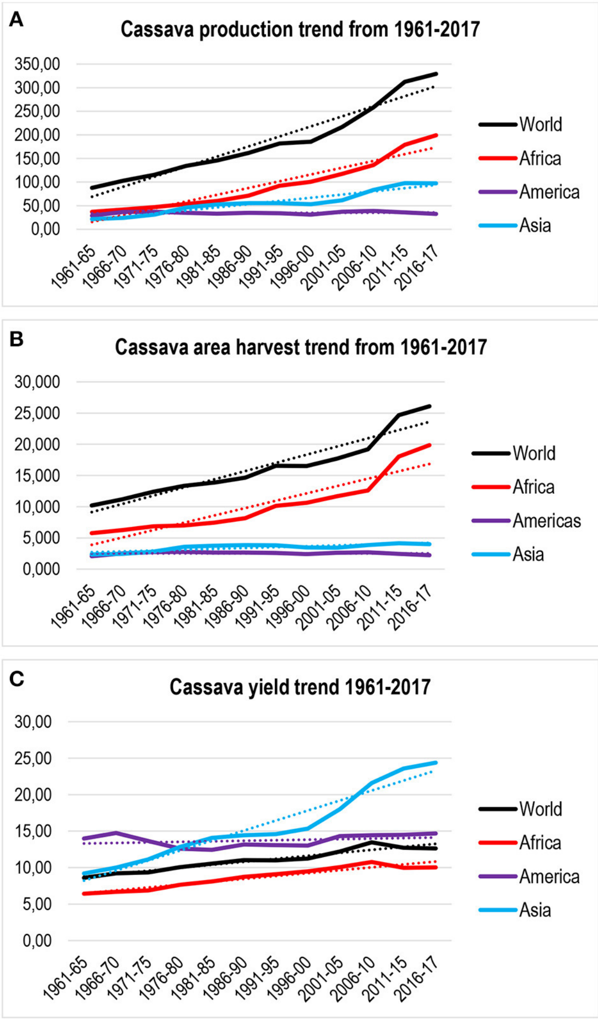

FIGURE 1 | Cassava production **(A)** area harvest **(B)** and yield **(C)** trend from 1961 to 2017 (Source: FAOSTAT, 2019).

industrial crop. In Africa, the demand for cassava production has been driven by its food applications, while in Asia the demand has been driven by its industrial applications for starch, livestock feed and biofuel production.

Although cassava has had a long history in the rest of Africa, its production in South Africa is a recent development, arising with the advent of production of high-quality industrial starch from cassava on an industrial scale. In South Africa, cassava is produced on a few commercial farms of <5,000 hectares and in small fragmented areas, with limited technologies and under low input farming system (Bunce, 2019). It is grown as a secondary crop by smallholder farmers and is utilized for the production of commercial and food grade starch. The sub-sector is dominated by disease-prone varieties with long maturation periods of more than 18 months, and low yield potential. However, cassava farming is becoming more attractive due to the diverse use of cassava products in the country and the diminishing potential of other crops such as sugar cane.

CASSAVA UTILIZATION

Cassava as Food Security Crop

Cassava is an important root crop and is a source of dietary energy to over 700 million people in the tropical and subtropical Africa (Prochnik et al., 2012). Cassava is the fourth most important source of calories in the developing world after wheat, maize, and rice. More than 40% of Africa's population consume cassava as a staple food, and it is the second most important crop after maize (FAOSTAT, 2019). The roots and leaves are the two most valuable parts of the mature cassava plant that can be used as a food source (Morgan and Choct, 2016). Cassava is grown primarily for its enlarged storage roots, which are consumed as food for humans in various forms (Chandrasekara and Kumar, 2016). Cassava roots are rich in carbohydrates and are a good source of energy, a moderate source of minerals and vitamins, and a poor source of proteins (Montagnac et al., 2009). In particular, cassava is a good source of Vitamin C, thiamine, riboflavin, and niacin (Montagnac et al., 2009). Cassava has the potential to produce and store more carbohydrate per unit area under production than any other major grain and root crops (El-Sharkawy and De Tafur, 2010). Cassava roots can be converted into many food products, such as chips, pellets, pasta, flour and starch, with good storability and relatively low postharvest losses (Adelekan, 2010). The nutritious leaves can also be harvested for human consumption as a green vegetable (Montagnac et al., 2009) and for animal feed (Lukuyu et al., 2014). The leaves are rich in iron, calcium, vitamins, and a good source of proteins (Montagnac et al., 2009).

Cassava storage roots can be stored in the ground for up to 2 years after maturity, and can be harvested at any time of the year when a farmer needs food (Sanchez et al., 2013). The natural high storability of cassava compared to other root crops provide farmers the opportunity to capitalize on the best market opportunities (Hershey et al., 2012). Farmers can plant and harvest cassava without any capital input on marginal lands where other crops cannot be produced. Cassava is grown predominantly by small-scale farmers with limited resources on marginally fertile soils (Kintché et al., 2017). The low input land use systems (also commonly referred as small-scale agriculture), which they operate on a sustainable basis is of great benefit to resource poor farmers and to the eco-system (Altieri et al., 2012). Consequently, cassava is considered as an excellent food security crop and a household food bank that can be drawn anytime when adverse climatic conditions limit the production of other crops (Nakabonge et al., 2018).

However, high cyanide content, poor protein, and micronutrient content, and pest and disease issues are the major problems in using cassava as a food crop. Serious malnutrition problems have been reported in countries that rely primarily on cassava food products, with little or no protein supplements (Akinola et al., 2020). Micronutrient deficiencies present in some staple food crops have been improved *via* bio-fortification (Bouis and Saltzman, 2017). Cassava has been targeted for bio-fortification because of its unique geographical distribution (Talsma et al., 2016). There is considerable potential for enhancing the nutritional value of cassava through breeding.

Variation in cassava for carotene content (Ceballos et al., 2017), protein content (Carvalho et al., 2019), and micronutrient content (Burns et al., 2012) have been reported in the available cassava germplasm collections.

Although South Africa is often characterized by food self-sufficiency at national level, about 20% of the households' experience food insecurity, malnutrition, unemployment and poverty (Abdu-Raheem and Worth, 2011). The fact that cassava's ability to grow and provide reasonable yield in areas where environmental conditions and per capita resource levels are declining makes it an ideal candidate to be a food security crop. In addition, most South Africans have a relatively monotonous dietary system, mainly based on maize and bread starch, and protein such as chicken and milk. Diversification of the crop base that require low agricultural input such as cassava will improve food and nutrient security at a rural household level. Hence, cassava can stabilize food security by providing food for many households and serving as a cash crop as a source of industrial starch in South Africa. In South Africa, the role of cassava as food security crop needs to be viewed from dual perspectives; first through its direct contribution to household food security and second indirectly by being cash crop through raw material sold to the starch industry. Hence, discussing the industrial application is unavoidable while elaborating the role of the crop on food security.

Cassava as Climate Smart Crop

Global climate change and its impacts have been observed and reported (Miller, 2008). Changes in precipitation amount and patterns, temperature, atmospheric carbon dioxide level and water availability are indicators of climate change (World Bank, 2008). The global mean temperature has increased by $\sim$0.74°C over the last century (Miller, 2008) and 1.1°C by 2020. In some locations, an increase in the number of extreme hot days and a decrease in the number of extreme cold days have been observed (Singh and Singh, 2012). Likewise, changes in the intensity and patterns of precipitation have been witnessed as the Mediterranean region, southern Africa, and southern Asia had a decline in precipitation, whereas northern Europe, northern and central Asia, and the eastern portions of North and South America had an increase in precipitation (IPCC, 2007). These affect the length of crop growing period, development and yield (Cai et al., 2009). The climate change impacts on agriculture are unavoidable, hence implementing climate adaptation strategies are crucial to mitigate the negative impacts of climate change.

South Africa is a water scarce country where only 12% of its land are suitable for crop production (Donnenfeld et al., 2018). Most of South Africa's land surface (69%) is suitable for grazing and livestock farming. South Africa uses about 60% of its scarce water resources on irrigation to grow crops such as maize, potato, wheat, sugar cane, and sunflower (Baleta and Pegram, 2014). Climate change poses a significant risk to South Africa's water resources, food security, health, infrastructure, ecosystem functions, and biodiversity (Ziervogel et al., 2014). In South Africa, climate change projections have suggested that by 2050 mean national temperatures will increase by 5–8°C, with much reduced rainfall in the west and south of the country, and an increased risk of heavy rainfall events in the eastern parts of the country (Calzadilla et al., 2014). These will result in changes in rainfall patterns, evaporation rates, temperature ranges, reduced crop yields, and the emergence novel pests and diseases of crops and livestock (Calzadilla et al., 2014).

In addition to climate change, a decline in land quality due to soil degradation, soil acidification and land competition has dramatically increased the challenge of achieving national food security. Expanding the area of available arable land is not possible due to demographic pressure, urbanization and expansion of industries (Naab et al., 2013). Agricultural intensification has often been considered as the primary approach to meet the rising food demand. Enormous gains in agricultural production have been achieved due to agricultural intensification through rigorous utilization of fertilizers, pesticides, and irrigation (Mateo-Sagasta et al., 2017). The widespread application of synthetic fertilizers has generated varying degrees of soil acidification, groundwater contamination, and ecological degradation of the available arable land (Khan et al., 2018). Similarly, the worldwide chronic illness such as reproductive and birth defects, neurotoxicity, kidney and liver damage, high prevalence of cancer, and the emergence of more virulent strains of diseases and pests are related to excessive use of synthetic agrochemicals (Mossa et al., 2018). In South Africa, the commercial sector relies heavily on the use of irrigation, fuel, synthetic fertilizers, pesticides, and herbicides. Moreover, relatively few crops have occupied the major production areas and grown repeatedly year after year.

Climate change coupled with ecological degradation and water scarcity has curtailed food productivity, availability, accessibility, and quality at the national level. The above factors also aggravate the emergence of novel pests and diseases (Jones and Barbetti, 2012). The contemporary arrival of the fall army worm, which has destroyed maize, wheat and potato crops across Africa and Asia, is one of the negative impacts of climate change observed in South Africa (Amusan and Olawuyi, 2018). To ensure that the agricultural sector continues to play an important role in the economy, sustainable agro-ecological solutions should be implemented (Wezel et al., 2018). The implementation of eco-system-friendly, sustainable agricultural practices such as crop rotation and sequencing, integrated pest management, efficient water management, crop and varietal diversification and the use of well-adapted improved varieties are obligatory. Cassava is drought resistant and resilient to climatic changes, high temperatures, and poor soils, which makes it an important crop for the twenty-first century (Mupakati and Tanyanyiwa, 2017).

Cassava as Potential Bio-Fuel Feedstock

More than 90% of South Africa's primary energy is derived from fossil fuels that constitute 80% of the country's greenhouse gas (GHG) emissions (STATS-SA, 2018). About 77% of South Africa's energy needs are directly derived from coal, and 92% of coal consumption on the African continent is produced in South Africa (Baker, 2017). The heavy dependence on coal in South Africa is not only because coal is a relatively cheap source of energy, but also because South Africa has abundant reserves

TABLE 1 | Comparison of bioethanol production from different energy crops.

Crop	Yield (tons/ha/year)	Bioethanol conversion rate (L/ton)	Bioethanol yield (L/ha/year)
Sugarcane	70	70	4,900
Cassava	40	150	6,000
Sweet sorghum	35	80	2,800
Maize	5	410	2,050
Wheat	4	390	1,560
Rice	5	540	2,250

Source: Wang (2002).

(STATS-SA, 2017). Fossil-based transportation fuels have been recognized as the largest contributor toward GHG emissions (Perera, 2018). Many countries ratified the Paris Agreement to reduce annual global greenhouse gas (GHG) emissions to between 30 and 50% by 2030 to prevent a global temperature rise (Shepherd and Knox, 2016). South Africa has also endorsed the Paris Agreement, and committed to reduce the contribution of coal-generated power from 82% in 2016 to 31% in 2050, as outlined in the Integrated Resource Plan (IRP) of 2016. Further, much of the national budget is spent on fossil fuel; hence, there is a growing commitment to explore alternative energy sources such as the use of renewable energy and the conversion of biomass to bioenergy (Petrie, 2014). The increase in the price of fossil fuel, coupled with the need to reduce greenhouse gases emissions, have driven the search for renewable sources of fuels.

Bioethanol production requires a highly productive, sustainable supply of feedstock, and appropriate processing technology. Cassava, apart from its traditional role as a food crop, is recognized as a potential feedstock crop for the production of bioethanol (Marx, 2019). Cassava is an excellent feedstock for ethanol production: it is adapted to a wide range of growing conditions, especially to marginal environments; it can be planted and harvested all year round; and cassava can be stored as dried chips before processing (Nguyen, 2007). Bioethanol can be produced from cassava either from storage roots or the cassava waste stream. Cassava storage roots, on average contain about 35% dry matter content, with a starch content of between 70 and 85% (Benvenga et al., 2016). Wang (2002), in his studies of bioethanol production potential of six energy crops, reported that the annual yield of bioethanol from cassava is significantly higher than from other crops (**Table 1**). Yang et al. (2017) achieved an ethanol yield of 0.9 g ethanol/L/h through a combination of aerobic and anaerobic fermentation processes, while Wang et al. (2017) reported an ethanol yield of 11.43% (v/v). Marx and Nquma (2013) achieved a final ethanol yield of 530 L of ethanol per ton of unpeeled cassava roots, which translated into 2,400 L/ha.

Cassava wastes are also a potential source of bioethanol and organic fertilizer (Ekop et al., 2019). Cassava waste includes leaves, stems, pulp, fiber peels and sub-standard tubers that can be used as ethanol feedstock. The peels and stems comprise of 28% of the total dry matter and can generate more than 60% ethanol, indicating the potential use of cassava wastes for ethanol production (Nuwamanya et al., 2012). Elemike et al. (2015) also reported that, depending on the starch-to-ethanol process, cassava wastes can have a starch content as high as 60% (w/w).

Cassava as a Potential Industrial Crop

Cassava is the fourth most important source of plant-based starch in the world after wheat, maize, and potato (Sharma et al., 2016). The global demand for cassava starch is projected to be over 10 million tons by 2024 (Business wire, 2019). Technological advancements in the starch industry makes cassava an attractive source of modified starch such as food grade starch, and adhesive, paper, and textile grade starches (Adelekan, 2010). Cassava is thus considered to be a highly valuable industrial crop for the world today and in the future.

In South Africa, maize is currently the main crop used for food (37.4%), feed (39.8%), exports (17.9%), and industrial purposes (4.8%). It constitutes two-third of the commercial area planted in field crops, with an average annual production of ∼10–12 million tons (Greyling and Pardey, 2019). Maize is the source of about 95% of the local starch produced in South Africa. Competition between industries utilizing maize products has resulted in the failure of the local starch industries to meet the starch demand of the country. Hence, South Africa imports around 66,000 tons of starch products annually, of which more than 33% is cassava (tapioca) starch (UN Comtrade, 2019). Although South Africa's starch import volumes experienced positive and negative growth patterns during the period 2008–2017, cassava starch import volumes have consistently been higher than those of maize, wheat and potato (**Figure 2**). If cassava can be used as an alternative starch source to satisfy the domestic starch demands, this will reduce competition among staple food commodities and reduce the volumes of imported starch.

Cassava storage roots contain a starch content that is about 40% higher than rice and 25% more than maize (Tonukari, 2004). Cassava starch is the cheapest and preferred known form of industrial starch, including in South Africa (**Figure 2**). The estimated demand for cassava starch alone in 2004 was 20,000 tons per annum; this demand would require more than 300,000 tons of cassava for milling and about 26,000 hectares of land under cassava production. Grasping the industrial potential of cassava in the starch industries and setting up rural cassava producers will create sustainable income sources and improve the livelihoods of rural community. Cassava starch also fetches a higher price on the market than maize, potato, and wheat starch. South Africa spends more than R40 million annually to import various starches, of which 17% is for cassava starch (UN Comtrade, 2019). The country imports most of the cassava starch from Asia and a small portion from the USA (IDC, 2017). Producing industrial starch from cassava locally will satisfy local starch demands, avoid competition among staple food commodities, relieve the country's economy from foreign currency strains, and reduce import volumes.

The largest exporters of cassava are not necessarily the largest producers. Although Africa is the leading cassava producer globally, most of the cassava crop is consumed domestically and considered as a non-trade commodity. Nigeria, the DRC, Brazil and Indonesia are the top producers of cassava globally.

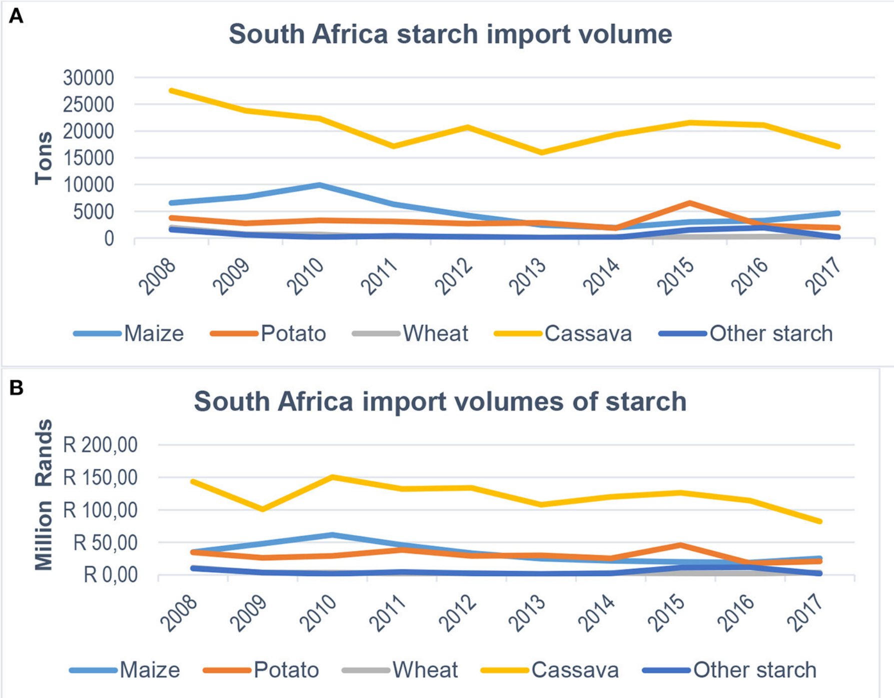

FIGURE 2 | **(A)** Starch import volumes into South Africa and **(B)** South Africa's import volumes of various starches (Source: Commodity Trade Statistics Database, United Nations Statistics Division, 2020).

Despite attempts to promote cassava as a commercial crop in Africa, low international prices for maize starch has made cassava starch production in Africa unattractive. Asia is driving the world trade in cassava starch, with Thailand at the top of the ladder, followed by Vietnam, Germany, and China (**Table 2**). At the beginning, European countries were the only cassava importers. However, imports of cassava products by non-European countries expanded in the mid-1980's mainly because other markets were developed in Asia (Otekunrin and Sawicka, 2019). Presently, China, USA, France, and Germany are the top cassava importers (**Table 3**). Two-sample t-test analysis was made to compare the differences between the changes estimated over the categorical times. There was a significant change ($p = 0.05$) in export volume between the period 2010–15 and 2015–17. South Africa sources its cassava supplies mainly from South East Asia. However, with appropriate investment, planning and policy support, this situation could be reversed.

Role of Cassava in the Development of Smallholder Farmer Community

Agriculture in South Africa has a dual character (Gwebu and Matthews, 2018), which comprises of relatively few well-developed commercial farms and a large number of small scale, subsistence farms. The commercial sector is mainly based on capital intensive, export oriented and large-scale production. They produce about 90% of the total agricultural production and their farms cover about 86% of the country's cropland. Subsistence farming, on the other hand, relies on traditional production methods and is labor intensive, employing about 86% of the total farm labor (Pienaar and Traub, 2015). Small-scale farmers mainly produce for household subsistence. Cassava provides an opportunity to improve smallholder farmers' income and food security by unlocking economic value, by opening up marginal lands for cultivation and pooling communal resources in addition to commercial operation by organized farmers groups to enable mechanization.

Cassava is a labor-intensive crop that requires lots of labor from planting to processing. Hence, it can provide employment opportunities to unskilled labor in rural areas. Moreover, cassava is a bulky and highly perishable crop that needs to be processed before it is transported, which opens up opportunities for small-scale farmers to be involved in producing semi-processed materials and simple value-added products, for greater economic gains derived from marginalized or nutrient poor land. Developing the cassava industry in South Africa could play a role in transforming smallholder sector into small- and medium- sized enterprises by engaging them in distributing better quality planting materials, implementing intensive cassava production and establishing community-based primary processing systems. Establishment of small-scale farmer development programs will ensure sustainable productivity and profitability of cassava production for small scale and emerging farmers. These initiatives could be used to drive the economic empowerment of small scale and emerging farmers through meaningful integration with the secondary processing industries. This will be achieved through partnerships that create an

TABLE 2 | World top leading starch exporters (in ton).

Country	2000	2005	2010	2015	2017	Changes (%)			
						2000–05	2005–10	2010–15	2015–17
Thailand	980,300	1,560,423	1,873,686	3,185,130	3,136,244	37	17	41	−2
Vietnam	89,436	344,747	1,080,648	2,200,250	682,702	74	68	51	−222
Germany	535,745	473,129	208,737	535,676	552,285	−13	−127	61	3
China	74,934	179,911	422,509	87,716	285,972	58	57	−382	69
Netherlands	391,108	317,126	306,249	168,756	151,015	−23	−4	−81	−12
Spain	73,154	37,618	127,324	153,538	150,906	−94	70	17	−2
USA	234,480	222,405	201,706	108,644	131,306	−5	−10	−86	17
France	95,551	129,496	102,350	77,270	79,713	26	−27	−32	3
Korea	68,802	62,067	104,292	63,597	49,728	−11	40	−64	−28
South Africa	44,996	38,492	35,919	32,847	30,248	−17	−7	−9	−9

Sources: FAOSTAT (2019).

TABLE 3 | World leading starch importers (in ton).

Country	2000	2005	2010	2015	2017	Changes (%)			
						2000–05	2005–10	2010–15*	2015–17*
China	151,520	609,576	979,658	2,081,646	2,572,161	75	38	53	19
USA	145,702	165,885	196,854	317,213	337,441	12	16	38	6
France	167,104	155,503	180,621	187,753	264,783	−7	14	4	29
Germany	186,969	282,068	346,557	413,702	258,495	34	19	16	−60
Netherlands	87,728	109,305	172,681	226,338	255,908	20	37	24	12
UK	168,083	177,042	224,162	238,037	254,524	5	21	6	6
Poland	6,169	38,822	110,897	177,642	160,129	84	65	38	−11
Indonesia	162,607	623,328	921,862	686,561	136,201	74	32	−34	−404
Malaysia	136,201	187,332	298,305	291,064	91,632	27	37	−2	−218
Belgium	96,373	126,758	98,212	120,065	59,318	24	−29	18	−102
South Africa	11,776	32,296	32,087	35,484	28,163	64	−1	10	−26

Sources: FAOSTAT (2019).
**Significant different at 5%.*

enabling environment by closing all gaps in the value chain. The source of the innovative technologies for technology diffusion and deployment will be the developmental funding institutions as well as research councils.

THE NATIONAL CASSAVA R&D STRATEGY: BACKGROUND ON STRATEGIC IMPERATIVES

In South Africa, the agricultural sector is expected to play a vital role in alleviating food insecurity, poverty, malnutrition, and unemployment, while protecting the ecology. Agricultural R&D strategy has serious implications on the way agricultural research is designed, implemented, evaluated, disseminated, and utilized to generate innovations. In the twenty-first century, agriculture remains fundamental for poverty reduction, economic growth, and environmental sustainability in developing countries (World Bank, 2008). Although the scientific methods of doing research have not been changed substantially since the nineteenth century, the environment within which the discovery and innovation occurs changes constantly. Rapid changes have been taking place in the institutional landscape, global economy, farming sector, social structures, and the global and local food industries (Anandajayasekeram, 2011). That is why a constant revision of the R&D strategy of the ARC and that of the country will remain imperative, with respect to emerging challenges and societal needs, and integrating the R&D with the value chain. By taking the below key considerations into account, the ARC, in consultation with role players, developed a cassava R&D strategy. The components of the cassava R&D strategy include; germplasm acquisition, evaluation, conservation and breeding, agronomy, crop protection, socioeconomics, food science, postharvest and storage, mechanization, and agro-processing thematic areas.

Important Considerations in the Crafting of the R&D Strategy

Agricultural Sector

South Africa has ∼35,000 largely white, highly capitalized commercial farmers and around 2.9 million black subsistence farmers (Aliber and Hart, 2009). The commercial sector is producing around 95% of the country's agricultural produce on 86% of total agricultural land, while the smallholder sector is farming on 14% of agricultural land (Aliber and Hart, 2009). The smallholder sector is characterized by low productivity, labor-intensive cultural practices, use of traditional production techniques, and poor institutional support, largely (Louw, 2013). The smallholder sector has been neglected in terms of the distribution of economic assets, support services, market access, infrastructure, and income (Pienaar and Traub, 2015). The development of an appropriate R&D strategy that addresses food security, malnutrition, inclusion of smallholder farmer sector and unemployment has been given the highest priority within the ARC.

Climate Change

Climate change and agriculture have significant impact on each other. Climate change has a massive impact on all forms of agriculture. Agriculture contributes to climate change through greenhouse gas emissions and changes in land use such as deforestation. There is an urgent need to recognize the risk posed by climate change in agriculture and vice versa. In case of subsistence farmers, the risks are high: due to their high exposure and vulnerability to natural hazards; their dependence on rain-fed agricultural production systems; and their limited capacity to ameliorate stresses induced by climate change. As a result, climate change will increase their vulnerability, and exacerbate levels of food insecurity and malnutrition. Several climate adaptation strategies have been suggested to address the gradual impact and risk of climate change. Adoption of climate smart agricultural techniques and job creation in rural communities to increase resilience and to contribute to more sustainable food systems have been given top priorities among the adaptation strategies. To this effect, a holistic and comprehensive R&D strategy, cutting across various disciplines, is necessary to harmonize the relationship between climate challenge and agriculture.

Organizational Structure

According to the United Nations estimates, the current global population is 7.7 billion, and this is expected to reach 10 billion by 2050. Consequently, it has led to increases in food demand and consumption, and will keep undermining food insecurity in Africa. Both national and international agricultural research institutions should be strengthened and capacitated to leverage the global demand for food and nutrition. Suitable approaches should be designed to increase the efficiency, productivity and profitability of the agricultural sector. Many studies in the past indicated that a combination of institutional reorganizations and other productivity enhancing strategies, such as the use of improved inputs, mechanized production techniques and improved management practices, are required to increase production efficiency (Abass et al., 2013). Market and credit access, meaningful linkage between producers and processers, diversification of use in various manufacturing sectors, practical training, and high market information flow to relevant stakeholders will help move the sector toward true commercialization.

Market

Agricultural commodity and input prices are likely to increase substantially, resulting in changes to the structure and behavior of the agricultural global market and its competitiveness. Future developments in South African agriculture lie primarily on greater technical efficiency, exploring niche markets and value-addition within the established commercial sector, together with improving the productivity of the smallholder sector. Some countries have develop their cassava value chain exclusively for food consumption, and others exclusively for industrial applications. For example, cassava production in Africa and Latin America is mainly driven by food security motives, whilst in Asia it is driven by industrial application, as the primary feedstock for starch and ethanol production. Although cassava has huge potential in Southern Africa, the major challenge for cassava cultivation is access to markets and creating interest in new market opportunities. However, the existing market for cassava products in Southern Africa signals the high potential for growth in industrial starch production locally. Market signals serve as an incentive for investment by the private sector (Abass et al., 2013). There are some encouraging and positive initiatives on the utilization of cassava by the starch industry. Some concrete examples are given below.

Mondi South Africa is an enterprise that aims to encourage long-term economic empowerment and job creation by developing small businesses in Mondi's forestry value chain and surrounding communities. The company has identified the potential for planting cassava on a commercial basis, which would create an employment opportunity for people within the rural communities of the Mondi Forests area. They currently producing 15 000 tons of cassava starch annually, with the industry usage sitting at 25,000 tons (Maema Obakeng, personal communication).

Tongaat Hulett Starch is Africa's largest producer of high-quality starch, glucose and related products. They produce starch for local and international markets across Africa and around the world using maize as a raw material. They are interested in exploring cassava starch as a raw material to exploit potential cost saving benefits due to cassava starch's unique functional properties. They have also expressed their interest by funding cassava research projects conducted at WITS University.

Some of the world's largest alcohol beverage making companies are finding ways of tapping into the potential of cassava. Both SABMiller and Diageo have launched commercially made cassava-based beers in Africa over the past 2 years. SABMiller PLC (now called AB InBev) has launched two cassava beers in Africa, Eagle (Ghana), and Impala (Mozambique). The main objective is to source raw materials from local farmers mainly to reduce costs whilst contributing to rural economic development. They are committed to expand the initiative, the business and financial models developed for the rollout of the brewing facilities in other African countries. Similarly, National Starch is a global ingredient solution company aiming to deliver the high-quality ingredients that give sweetness, texture and nutrition for the food, beverage and brewing industry. Their local subsidiary has shown interest in sourcing cassava starch for their multinational client base.

PhilAfrica foods was established to transform the lives of millions of Africans economically and socially through food processing in Africa. Dadtco PhilAfrica, a Pan-African cassava processor, is a mobile starch processing company that produce high-quality wet and dry starch flour for primary use in the baking and brewing industries. They source raw materials directly from smallholder farmers in rural regions of sub-Saharan Africa, thereby significantly impacting the lives of thousands of farmers and their families.

Unilever, the Anglo-Dutch consumer goods company, is targeting cassava root to make sorbitol, a key ingredient in toothpaste and other products. Their target is to improve their local procurement content by sourcing the sorbitol locally.

The potential of cassava in animal feed has been studied extensively by researchers worldwide. Most parts of the cassava plant such as roots, stems and leaves can be used for animal feed. The major problems of cassava roots restricting its use in animal feeds are its low amylose content and protein content (0.5–1.7%), compared to other starch crops. However, the high-energy value of cassava makes it an attractive carbohydrate ingredient in animal diet (Morgan and Choct, 2016). There should be a market for cassava products in the existing domestic market for animal feeds in South Africa. The leaves are high in carbohydrate and protein (17%), and thus they can be used as a potential substitute for soybean cake, alfalfa, or maize.

The Roles of Private and Public Sectors

The role of private and public sector needs to be well-defined and this will facilitate commercialization of crop technologies from public sector research. The ARC initiated a process to coordinate the cassava R&D in South Africa in light of the growing importance of the crop, and the lack of coordination among the various stakeholders. Several stakeholder engagements have been made, aimed at mapping the way forward for cassava R&D and commercialization of the crop in South Africa. During the various stakeholder meetings, aspects such as the opportunity and challenges of cassava research, available resources in terms of manpower and research funds, promotion and adoption of the crop and policy issues that need to be addressed were raised and discussed. The stakeholder forum discussed the need for an integrated approach with strategic partnership between the public and private sectors. This can be realized through close linkage between producers, starch-processing industries, farmer support programs, financial institutions and agricultural research institutions along the cassava value chain. Similarly, collaboration among governmental organizations would aim to share resources and to make an enhanced impact on food and nutrition security, and to increase production, productivity, profitability, and environmental stability, and to stimulate job creation.

The ARC was given the assignment to assess the current research capacity for supplying high-quality planting material and farmer-based small-scale production of cassava tubers for commercialization of the crop. The ARC was also tasked to drive the policy initiative to develop an evidence-based policy that will facilitate the equitable economic exploitation of the crop. The Technology Innovation Agency (TIA) agreed to explore the industrial potential of the crop and to assess the availability of financial resources to support essential cassava research programmes. It is envisaged that these initiatives will produce the required result in developing a viable starch industry underpinned by sustainable primary production supported by strong R&D. Previous studies had been undertaken with the objective of establishing cassava as a source of industrial starch, most of which failed. The TIA- led initiative was constructed to mitigate the shortfalls of these prior studies, namely to access diverse, disease-free cassava material germplasm; to screen the germplasm in multiple geographic regions over multiple seasons and using the data from these cultivar assessments to determine the feasibility of adopting suitable cultivars by small scale or emerging farmers in a pooled communal set-up. The study will provide the starting point for a local breeding program to develop superior cassava cultivars for South Africa.

Alignment With Regional and International Research Community

Globally, cassava is recognized as an important food and industrial crop. The International Institute of Tropical Agriculture (IITA), International Center for Tropical Agriculture (CIAT), National Agricultural Research Institutes (NARs), and Universities in Africa have played leading roles in cassava improvement. The production, characterization and product development from cassava is at its infancy in South Africa compared to other African countries. It is vital that South Africa taps into the skills and advanced R&D programs of these institutions by establishing strong collaborative links. Capacity building can be done through fellowships, grants schemes, exchange and partnership programmes. Collaborative research in terms of information access, germplasm exchange and genotyping of elite germplasm should be imperative. In addition, to enhance the local knowledge base of cassava, formal training through postgraduate studies and informal trainings such as awareness creation among stakeholders and field days would be important.

DRIVERS OF THE CASSAVA INDUSTRY IN SOUTH AFRICA

Farmer Production System Training

The UN Conference on Trade and Development released a Policy Brief in 2010 suggesting that: "*In the Twenty-first century, transforming the existing industrial-agricultural systems into knowledge- and labor-intensive rather than agro-chemical and energy-input-intensive is necessary*" (Trade Development Report, 2010). The transformation should consider integration of local knowledge with modern agricultural techniques, giving strong emphasis to the available biodiversity and resources. A Trade Information Brief (TIB) for the Southern Africa Development Community (SADC) (2015) proposed cassava as a potential industrial crop for SADC's farmers. Although cassava has not been a traditional commodity in South Africa, exploiting cassava's potential for food, industrial starch and renewable energy will improve the livelihood of many farmers at a household level. Training is an integral part of any development activity and a process by which acquiring new knowledge, skills, practices, and attitude in the context of preparing farmers for improving agricultural productivity (Pandey et al., 2015). Training plays a key role in human capacity development, to equip farmers with skills, knowledge and competencies for sustainable crop production, resource utilization, and income generation (Yaseen et al., 2015). Therefore, adequate training on cassava production, processing and marketing is essential for farmers to acquire the necessary knowledge and skills to exploit the full economic potential of the crop. Accredited training modules in cassava production and processing, as well as financial and business management, will be developed. Production enterprises will have to be established and supported to enable farmers to produce and partially process products for the starch processing market.

Awareness Creation and Promotion of the Crop

The local production of the staple commodities such as maize, wheat and potato is affected by recurrent and severe droughts. Exploring alternative climate resilient solutions have become a priority. Awareness creation of the prevailing environmental conditions and the available mitigation strategies are imperative. As part of awareness creation, organization of symposia, conferences and workshops, at which researchers from local and international institutes can present their research findings on cassava should have a significant impact. These conferences can serve as essential forums to inform key policy makers, farmers, growers and processors to access first-hand information from experts in countries where cassava is a major crop. Funds should be accessed from national and international institutions. Furthermore, the use of a promotional hub is vital to introduce various cassava products to researchers, policy makers, producers, and processors to appreciate the economic importance of the crop.

Development of Suitable Business Model

The social enterprise model is a corporate model that addresses the social, environmental and economic aspects of any commodity development. In this model, the farmers are organized in a way that they play a key role in leading the primary production aspect, but are also stakeholders of downstream processing. The primary objective of the social enterprise model is to make farmers involved beneficiaries across the entire value chain. It is critical to develop the whole value chain in such a way it sustains itself and empowers farmers. One of the merits of this model is that it is socially viable as the majority of the society around the production area benefits from an environmentally sustainable production system. Second, cassava, being a multi-purpose crop, has production, processing and marketing components that provide job opportunity to the smallholder farmers across all the value chain. However, there is no example of feasible and successful agricultural social enterprise in South Africa that can be used as a model. However, it has been used successfully in other sectors such as education and training, according to a study done by the Gordon Institute of Business Sciences at the University of Pretoria (GIBS, 2018).

The Role of Commodity Organization

A commodity-based organization represents the entire value chain such as growers, consumers, processors, traders, importers, exporters, input distributers, and transporters. These types of organizations can play important role in promoting the particular interests of their members and advocating policy and regulatory changes. The South Africa cassava industry association (CIASA) was established under the Department of Trade, Industry and Competition (DTIC) to address and coordinate all aspects of the cassava value chain (IDC, 2017). Presently, even though CIASA attempts to be proactive, it was not be able to coordinate cassava research or the development of a cassava value chain in South Africa. The association was probably established too soon, when there was a lack of critical mass and political support. CIASA should be revived and strengthened to represent the cassava value chain in SA and the full spectrum of stakeholders. It was suggested, during a workshop with R&D stakeholders, that the constitution of CIASA should be revisited and its role should be redefined to support the cassava industry in SA as a whole, including researchers, which were not considered by the DTIC. DTIC included cassava starch in the 2016/2017 Industrial Policy action plan (IPAP) to promote trade activities in the industrialization of cassava, which was informed by the consultations leading to the establishment of CAISA.

Market Creation and Product Diversification

Although the current demand for food cassava is small in South Africa, there is the potential to develop cassava products that are affordable and attractive to consumers in South Africa. Brazil has developed a wide range of cassava food products, and benefits from a strong domestic market (Demiate and Kotovicz, 2011). High-quality cassava flour can be used as a wheat flour substitute in bread, pastries, cookies, and biscuits and as a source of food starch. Because of cassava's huge potential in the global starch market, the focus should be on the production of high-quality food starch, as well as lower value industrial products.

Investment in Processing and Product Development Enterprises

The cassava value chain starts with the production of certified planting materials, followed by primary production, and on-farm processing for the production of semi-processed products, prior to industrial processing. The development of the cassava industry can contribute to food and income security, job creation and revitalization of the rural sector. It can help address the challenges of the high starch demand and provide an avenue for import substitution. The processing industries have a key role in driving cassava development and to engage small and large starch processing enterprises in South Africa. Investment in cassava processing and product development should rely on systematic analysis of opportunities and constraints of cassava at each stage of the commodity development cycle. This can be done by stakeholders that are engaged in the development of the cassava industry that involves producers, processors and consumers, as well as associated national, international and non-governmental organizations. Research and development support is essential to assist to overcome important problems within the production-processing-marketing continuum.

RISK FACTORS

Frost

Cassava being a tropical crop, it is highly sensitive to low temperatures below 18°C (Huang et al., 2005). Low temperature causes delayed sprouting of stem cuttings, reduced leaf expansion, low biomass accumulation and decrease storage root yield (Phoncharoen et al., 2019). In South Africa, the growing season is characterized by a hot rainy summer followed by a cold and dry winter. Frost is a major obstacle for cassava production and propagation in South Africa. There are two approaches used by researcher to cope with frost, namely the use of early bulking germplasm or pruning. All the varieties currently in the system are old cultivars that take more than 18 months to mature. Therefore, early bulking cultivars that fit into the growing season (i.e., matures within 7–9 MAP) or cold-tolerant cultivars that can grow in a prolonged growth period are in demand. The Brazilian climatic condition is similar to South Africa. In the higher altitude and moisture prone areas of Brazil, farmers grow cassava in October/November and prune the cassava plant in June to avoid the cold winter. There is variation in cultivars response to pruning in terms of root yield, starch and dry matter content. Some cultivars show a reduction in root fresh yield, dry matter and starch content due to the fact that cassava plants consumed the reserve starch to overcome vegetative bud dormancy during the winter and shoot regrowth during the summer, while other continued the starch accumulation from where it stops with no reduction in yield and starch related traits (Curcelli et al., 2014). These materials are considered to be frost tolerant.

Viral Disease

Cassava production in Africa is curtailed by cassava mosaic disease (CMD) and cassava brown streak disease (CBSD) (Legg et al., 2015). CMD is a severe cassava disease prevalent in all cassava growing regions of Africa and India (Legg et al., 2011). However, variation in overall prevalence and in the severity of losses caused by the disease has been reported among regions (Ntawuruhunga et al., 2007). CMD is caused by a complex of diverse whitefly-transmitted cassava mosaic geminiviruses (CMGs) (Patil and Fauquet, 2009). The cassava geminivirus family is composed of at least 11 distinct viruses that have been characterized worldwide, of which seven have an African origin (Kuria et al., 2017). Generally, in Africa the estimated yield losses caused by CMD were reported at 15–24%, representing 15–28 million tons of cassava production (Masinde et al., 2016). The estimated annual economic losses in East and Central Africa are estimated to be between $1.9 and $2.7 billion USD (Patil and Fauquet, 2009).

Cassava brown streak disease (CBSD) was restricted to the lowland coastal areas of eastern Africa (Patil et al., 2015). Recent surveys have shown that CBSD is highly prevalent in Central, Eastern and Southern parts of Africa (Mulenga et al., 2018). It has been reported in Mozambique, Kenya, Uganda, Zambia, and Malawi (Tomlinson et al., 2018). The study by Mbewe et al. (2017) indicated the presence of two distinct virus species. CBSD does not have an obvious effect on the growth of cassava; however, the root necrosis produced by CBSD has caused a reduction in both qualitative and quantitative yield (Alicai et al., 2007) and affects maintenance of planting materials (Ndyetabula et al., 2016). Most of the yield loss from the disease is thought to be the consequence of the loss of root storability resulting from severe root rot (Hillocks et al., 2008). Gondwe et al. (2003) reported 18–25% yield loss by CBSD, while Hillocks et al. (2001) published a yield loss estimate of 70% from the most susceptible variety. Much less attention has been given to the disease compared to CMD, partly due to its restricted geographic distribution. However, recently the high prevalence and distribution of the disease has been reported due to presence of high population of whitefly vector B. tabaci.

Market Access

In South Africa, market access remains one of the key limiting factors for the development of emerging commercial and smallholder farmers; some institutional and technical constraints to market access in SA are well-documented (Van Schalkwyk et al., 2012). The Market for agricultural produce is largely controlled by a handful of corporate companies with excessive regulatory and compliance requirements that are beyond the means of emerging farmers. To exploit the socio-economic potential of cassava, unlocking market access and developing the entire value chain are critical. Work must start on the following key aspects to ensure the creation of sustainable market;

- Promoting the crop and ensure buy-in for primary production for food and industry,
- Understand the socioeconomic and technical production barriers,
- Organize critical mass of primary producers capable of sustainably supplying cassava raw material for starch processing industry
- Ensure farmers have access to improved varieties and production technologies that provide competitive advantage against other starch crops
- Ensure the processing industry is developed simultaneously and there exists a mutually beneficial off-take agreement and
- Introduce legislative mechanisms that favor local production and import substitution.

The ARC has already embarked in some of the aspects described above. It should be noted that there are encouraging signs that there are farmers and farmer groups ready to embark on cassava production and beneficiation. The Authors of this article have received request for production support in the form of variety choice and agronomic support in Limpopo, KwaZulu-Natal province and Mpumalanga provinces. However, ensuring market access has paramount importance before large-scale production is resumed.

CONCLUSION

Cassava can grow and produce reasonable yields in areas where cereals and other crops are not viable. It can tolerate drought and can be grown on soils with low soil fertility, but responds well to irrigation and fertilizers. Cassava is highly flexible in its management requirements and has the potential to produce more calories per unit area of land than other crops. It is relatively resistant to major pests and diseases that affects major staple crop and be bred to tolerate the two major viral diseases with little or no yield loss. Cassava yields can be as high as 70–80 t ha^{-1} at research stations, although national yields are well below these levels and the global cassava yield is <12 t ha^{-1}. The harvesting of cassava can be delayed for months, with the result that it has been used in developing countries as a famine reserve and food security crop. Delayed harvesting allows farmers to access markets when supply is low and prices peak. Although cassava has been considered as a poor man food crop, it has the potential to develop as a major industrial crop in Africa. Cassava starch has some unique characteristics that favor its use in specialized market niches.

Exploiting the industrial potential of cassava in South Africa will improve rural livelihoods through income generation and job creation. Furthermore, the national economy should benefit indirectly from job creation, and directly from foreign exchange savings originating from replacing imported products and raw materials.

The key to exploiting the full potential of cassava largely lies in establishment of national R&D strategy that focus on satisfying the local starch demand in the short term and export oriented starch production in the long ran.

A demand-driven approach should be implemented in research and development programmes to support the production and processing of cassava. Hence, it is critical that a long-term, multidisciplinary R&D programme should be established to support all facets of the cassava industry.

Development of strong value chains is vital in order to integrate cassava into the current production system; this however, should ensure primary producers remain as part of the value chain to incentivise production as opposed to the mere producers of raw material.

Implementing intensive out growers production system for small-scale farmers is imperative together with farmer support program.

The roles of private and public sector need to be well-defined and alignment with regional and international research community should be emphasized.

Currently, there are no improved cassava cultivar available in South Africa and the available varieties are vulnerable to diseases and have long maturity periods (>18 months) and low yields. Germplasm with high yield potential and resistance to biotic and abiotic stress factors should be imported, characterized and bred for local conditions to ensure the sustainable primary production of cassava.

AUTHOR CONTRIBUTIONS

AA designed, initiated and managed the project and contributed to manuscript preparation. MB, OM, SV, and ML contributed to manuscript preparation and edition.

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Conflict of Interest: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

frontiers in Sustainable Food Systems

ORIGINAL RESEARCH
published: 30 April 2021
doi: 10.3389/fsufs.2021.664253

Examining the Barriers to Gender Integration in Agriculture, Climate Change, Food Security, and Nutrition Policies: Guatemalan and Honduran Perspectives

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Specialty section:
This article was submitted to Climate-Smart Food Systems, a section of the journal Frontiers in Sustainable Food Systems

Received: 04 February 2021
Accepted: 24 March 2021
Published: 30 April 2021

Citation:
Howland F, Acosta M, Muriel J and Le Coq J-F (2021) Examining the Barriers to Gender Integration in Agriculture, Climate Change, Food Security, and Nutrition Policies: Guatemalan and Honduran Perspectives. Front. Sustain. Food Syst. 5:664253. doi: 10.3389/fsufs.2021.664253

Gender mainstreaming is seen, at international level, as critical to achieving national development goals and addressing key global challenges such as climate change and food and nutrition insecurity in the agriculture sector. Our study examined the barriers leading to poor gender mainstreaming and potential solutions in policies applying to gender, agriculture, climate change, food security and nutrition, in both Guatemala and Honduras. We used a case study approach to analyze the barriers to gender integration in these governments' policies. Based on semi-structured interviews and policy document analysis, we conducted a methodology based on policy mix, policy integration and policy translation. Results show that, despite having made multiple international commitments on gender issues and having gender-labeled policy and governmental gender bodies, gender mainstreaming in the policy cycle is lagging. There are multiple barriers of a different nature and at different levels that explain the lack of gender integration in the policy cycle, related and linked to: (1) policy translation from the international level; (2) structural policy barriers at national level; (3) behaviors and corruption; and (4) lack of knowledge and capacity. Solutions to address these barriers have been identified. Our results confirmed the literature findings and also introduce new elements such as the importance of considering the nature of the relationship (purely technical and/or political) between governments and international cooperation actors to evaluate the level of gender integration in policy. Furthermore, we stress that for key informants, there are no (easy) solutions to redress the poor gender integration strategies implemented. Finally, we noted that no solutions were provided relating to structural racism and machismo, religious extremism, power groups, and censorship of civil society.

Keywords: gender mainstreaming, policy integration, climate change, food security and nutrition, agriculture

INTRODUCTION

Achieving effective gender mainstreaming in the design, implementation, monitoring and evaluation of policies is considered, by academics and international organizations, as critical to meeting national development goals (FAO, 2011; Bryan et al., 2016; Njuki et al., 2016; CDKN, 2017; Kristjanson et al., 2017; IICA, 2018; Gutierrez-Montes et al., 2020), and to reducing food insecurity and malnutrition (FAO, 2011; IICA, 2018). The gender and development literature has extensively researched and emphasized the importance of considering the nexus between gender, agriculture, food security and nutrition (FSN), and climate change (CC) (Beuchelt and Badstue, 2013; Bryan et al., 2017b; Howland et al., 2019), not only to reduce gender inequalities, but also to address CC and FSN issues (UN-Women, 2015; Jost et al., 2016; Murray et al., 2016; Nelson and Huyer, 2016; Njuki et al., 2016; Bryan et al., 2017a; IICA, 2018). However, few studies address the process of gender integration in the policy cycle related to the nexus of gender, agriculture, FSN, and CC (Gutierrez-Montes et al., 2020). In this paper we explore the barriers for gender mainstreaming in agriculture, climate change and food security policies.

For agricultural policies, gender considerations are particularly relevant, considering this sector is the most important source of employment for women in rural areas in most developing countries (FAO, 2011). However, despite women's important contribution to the agriculture sector, they have less access to resources in terms of assets, inputs, land, education, financial services, technologies, and decent employment opportunities (FAO, 2011; Coello et al., 2015; IICA, 2018; Gutierrez-Montes et al., 2020). These gender inequalities have a direct effect on aspects such as agricultural productivity. Depending on the country and the crop, the gender productivity gap can vary between 4 and 25% (FAO, 2011; UN-Women, 2015). Rural women are also more likely to receive lower wages than men (FAO, 2011) and female-headed households are more vulnerable to economic shocks and more likely to fall into poverty than male-headed households (IICA, 2018).

On another hand, women play an important role in the three pillars of food security and nutrition (FSN), namely (1) *food availability* (consistently sufficient quantities of food available); (2) *food access* (sufficient resources to obtain appropriate foods for a nutritious diet); and (3) *food use* (appropriate use, based on knowledge of basic nutrition and care, as well as adequate water and sanitation) (Njuki et al., 2016). Regarding food availability level, closing the gender gap in agriculture could reduce hunger between 12 and 17% in the Latin America and the Caribbean (LAC) region (IICA, 2018). At the food access and food use level, when women control additional income, they spend more of it on food than men do (FAO, 2011). In Central America, women-headed households whose male partners have migrated have the highest levels of food security and food diversity compared to other groups, suggesting that money controlled by women is allocated at greater rates toward family nutrition (Coello et al., 2015). However, despite their important contribution to each of the three pillars, women are also highly affected by food insecurity and malnutrition (Njuki et al., 2016).

In the context of climate change (CC), gender issues present both opportunities and challenges regarding increasing agricultural productivity and farmers' resilience to CC, and improving livelihoods (Kristjanson et al., 2017). Climate change poses a major challenge; it is expected to aggravate social discrimination, worsening people's situation in general, and of women in particular, because of the gender gaps that remain in the agricultural sector (Adger, 2003; CDKN, 2017; Gutierrez-Montes et al., 2020). Climate change could thus undermine the progress made in terms of gender equality (CDKN, 2017). However, gender-sensitive CC interventions and programs (those that acknowledge the differentiated and negative impacts of CC on women and men and propose equitable and sustainable measures for both genders, according to their respective roles and tasks) also present an opportunity to design interventions that are better targeted to the needs of rural women and men, potentially overcoming barriers to implementation (Bryan et al., 2016, 2017a).

In the context of a changing climate, failing to address the gender gaps in agriculture not only directly impacts the lives of rural women, but also reduces average yields, and leads to over-cultivation, soil erosion, and land degradation (UN-Women, 2015). In this way, addressing gender gaps has paramount effects for the agricultural sector and for the economy in general (FAO, 2011). It has been estimated that closing the gender gap could increase agricultural productivity in the developing world by 2.5% to 4%, on average (FAO, 2011), as well as address current and future challenges in productivity (FAO, 2011; Kristjanson et al., 2017).

Within this context, the gender and development literature has extensively researched and emphasized the importance of considering the nexus between gender, agriculture, FSN, and CC (Beuchelt and Badstue, 2013; Bryan et al., 2017b; Howland et al., 2019), not only to reduce gender inequalities, but also to influence how CC, and food and nutrition insecurity issues are addressed (UN-Women, 2015; Jost et al., 2016; Murray et al., 2016; Nelson and Huyer, 2016; Njuki et al., 2016; Bryan et al., 2017a; IICA, 2018).

At an international scale, two processes that are ongoing and interlinked have shown their growing influence on practices, institutions, and policy narratives at national levels (Kennett and Lendvai, 2014). First, economic globalization has increased inequalities between men and women, and second, powerful supranational actors have risen and devoted their attention to human and environmental rights issues (True and Mintrom, 2001). In this context, several agreements have been reached and adopted to foster gender equality in development policies (Beijing Platform for Action), to address CC (Paris Agreement/COP21), and food and nutrition insecurity issues (Global Nutrition for Growth Pact "Nutrition for Growth").

Even though different approaches and methods have been developed to assess CC and FSN issues (Ampaire et al., 2017; CEPAL, 2018), and to assess gender and CC issues (Gumucio and Tafur, 2015; Bryan et al., 2016; Kristjanson et al., 2017; Acosta et al., 2019a, 2020; Ampaire et al., 2020), considerably less attention has been devoted to methodologies and frameworks that assess gender and food insecurity issues in policies and interventions. As explained by Bryan et al. (2017a) gender and nutrition issues are rarely addressed in the resilience literature. Conceptualization of the links between gender, CC, FSN, and agriculture have been also elaborated (Beuchelt and Badstue, 2013; Bryan et al., 2017b). However, these frameworks do not specifically assess gender integration in policy design and implementation and, consequently, no specific methodology has been developed to assess gender integration in CC, FSN, and agricultural policies.

This study seeks to bridge this gap. Through policy document analysis and key informant interviews we examine the barriers that result in poor gender mainstreaming in CC, FSN, and agricultural policies and explore possible solutions, using the cases of Guatemala and Honduras.

Guatemala and Honduras provide us with very relevant cases on these issues. On the one hand, the two countries have made international commitments related to gender integration in policy, and their governments have elaborated gender policies at national and sectorial levels (e.g., agriculture) and created gender bodies in charge of coordinating gender mainstreaming/gender policy implementation. On the other hand, as in many countries, the implementation of gender policies and mandates have been disappointing. Despite a strong international context on gender, and the fact that gender mainstreaming has been broadly adopted in many countries' national policies, gender inequalities have not been systematically addressed on the ground (Acosta et al., 2019a), hence the disconnect between policy and implementation.

Our study seeks to address the following research question: *What are the main barriers to and solutions for gender integration in policies and interventions tackling food insecurity, nutrition, climate change and agriculture in Guatemala and Honduras?* In so doing, we examine whether both countries present similarities, and/or whether there are context specificities to the limited effects of gender mainstreaming in these policies for each of the countries.

CONCEPTUAL FRAMEWORK

This paper is based on the conceptual framework proposed by Howland et al. (2019), which examines gender integration in agriculture, CC, and FSN policies and interventions using three main concepts, namely: (1) policy integration (Van Bommel and Kuindersma, 2008), (2) policy mix (Flanagan et al., 2011); and (3) policy translation (Acosta et al., 2020). In this section, we present an overview of each of these three concepts, highlighting their relevance for and their application in this study.

Following Van Bommel and Kuindersma (2008), "policy integration" refers to the incorporation of an issue in policy making and policy evaluation. This concept is often used interchangeably with mainstreaming [see e.g., Nunan et al. (2012), Brouwer et al. (2013)]. As mentioned by Tosun and Lang (2017), the concept of policy integration was first mentioned in the context of gender equity, education, and anti-poverty policies (see e.g., Jacquot, 2010). And it has increasingly been applied to assess CC and the environment governance (see e.g., Visseren-Hamakers, 2015). It has been used to understand policy-makers' motivation for promoting integration, to analyze the design of legal instruments, or evaluate the performance of policy integration (Tosun and Lang, 2017). Van Bommel and Kuindersma (2008) consider policy integration crucial to address boundary-spanning challenges, such as gender issues, to achieve policy objectives and to avoid contradictory policies. We therefore defined gender integration as the process of incorporating gender issues into the process of policy making and evaluation for agriculture, CC, and FSN. For our purpose, we rely on the policy integration concept to capture the level of integration of gender issues. We consider integration at all stages of the policy cycle from elaboration, to implementation and evaluation (Laswell, 1956). Following Candel and Biesbroek (2016), we use two dimensions to capture the degree of (gender) integration. The first dimension refers to the subsystem involvement, which corresponds to the range of actors and institutions involved in the governance of a particular cross-cutting policy problem (here, gender equity). The second dimension concerns the policy goals, which refers to the explicit adoption of a specific concern within the policies and strategies of a governance system, including its subsystems, with the aim of addressing the concern (here, gender equity). To characterize the first dimension, we consider in the current institutional layout addressing gender, climate, FSN, and agriculture issues, and the gender-specific office or administrations as an indicator of gender integration (True and Mintrom, 2001). For the second dimension, we assume that the level of gender integration within policy documents constitutes a signal of the likely extent of achievement of gender objectives (Gumucio and Tafur, 2015). We also used the concept of integration to systematically frame our questions during interviews with key informants for them to identify barriers and solutions at each stage of the policy cycle (beyond policy design).

The concept of "policy mix" captures the interactions between relevant policies affecting a boundary spanning challenges in a specific space and time (Flanagan et al., 2011). It also enables us to the analyze the coherence of the interaction of policy instruments (instruments mix) to achieve a specific goal. Policy mix acknowledges that policies of different domains have different objectives, which can be in synergy or tension with achieving an overarching goal (here, gender equity). Indeed, academia recognizes that governments rarely address policy goals through a single policy instrument; instead, policy mixes consisting of multiple goals and instruments tend to develop over time, especially where jurisdiction over policy issues is shared among agencies or levels of government (Del Rio and Howlett, 2013). In our case, we considered gender equity as our boundary-spanning challenge, and the scope of our analyzed policy mix includes the policy domains of gender, CC, FSN, and agriculture. Analyzing policy interactions can furnish a more holistic understanding of how policies included in the policy mix affect gender equity. Indeed, the policy mix concept opens the scope of analysis beyond gender-labeled policies to see if, effectively, gender is integrated within agricultural, CC, and FSN policies.

The issue of gender integration has been promoted by international arena toward national or local arena, especially in less developed countries (Acosta et al., 2019a). Hence "policy translation" is one of the processes affecting policy integration (Acosta et al., 2019a). As shown by Acosta et al. (2020), the process of translating international gender norms to the national sub-national levels is one factor that explains the obstacles to effective gender mainstreaming and the implementation gaps. In fact, gender standards formulated and defined at the international level can compete with other standards at the national or local levels (Acosta et al., 2019a) or be over-simplified through multiple translation processes (Kennett and Lendvai, 2014). In Acosta et al. (2019a), the translation of norms is described as a process of negotiation and adaptation in which meaning is configured and reconstructed to fit a specific discursive and normative context. The translation of international standards involves both a translation of narratives, through which international standards are translated into domestic standards, and a translation of domestic standards into policy instruments, such as budgets (Acosta et al., 2019a). As also explained by Kennett and Lendvai (2014), the concept of translation is a means to explore the ways in which policies move and transform between sites, places, people, and scales. Therefore, for this study that analyzes two different countries in the same region, it is relevant to incorporate the policy translation concept for a better understanding of the potential barriers to gender integration in policies related to CC, agriculture, and FSN during this translation phase. In the Results, we show the importance of considering the policy translation process of the gender concept, propelled from the international level, to understand barriers to gender mainstreaming in our policy mix at national levels.

METHODOLOGY

Case Study Selection

This study follows a case-study approach (Yin et al., 2002; Flyvbjerg, 2006). Honduras and Guatemala constitute critical case studies for the examination of the effectiveness of gender integration in agriculture, FSN, and CC policies. Critical case studies are defined as having a strategic importance in relation to the problem under study (Flyvbjerg, 2006). Firstly, both countries are highly dependent on agriculture, with more than 50% of their population living in rural areas (FAO, 2016). In Honduras, subsistence, low-productivity agriculture is the most representative in the country and women are involved in most of these production processes (e.g., cutting coffee, tobacco processing, growing vegetables and basic grains, tending the garden, and marketing fish products) (JICA, 2011). In addition, women develop small- and medium-sized agricultural and artisanal enterprises and participate in the processing of artisanal fishery products (JICA, 2011). In Guatemala, women are incorporated young into the rural economy (20% of under 15-year old) and participate actively in creating local livelihood alternatives (Ballara et al., 2012). However, women's integration in agriculture is not equitable since women receive lower incomes, are not properly accounted for in government statistics, and enjoy less access to land, credits, and inputs (Ballara et al., 2012; IICA, 2018; Gutierrez-Montes et al., 2020).

In the LAC region, CC and climate variability are particularly expected to adversely affect the Dry Corridor ("Corredor Seco") (IPCC, 2014). Within the Dry Corridor, Guatemala and Honduras are the most exposed (together with Nicaragua) to drought, floods, and landslides, among other extreme climate events (IPCC, 2014; FAO, 2016; Central American Agricultural Council (CAC), 2017). These changes could affect agricultural productivity and threaten the food and nutrition security of the poorest populations on the one hand, and exacerbate future health risks on the other (IPCC, 2014). The effects of CC and climate variability will also be distinct for men and women farmers. For example, research has shown gender-differentiated vulnerability levels to climate shocks stemming partly from women's and men's different roles in agriculture (Bryan et al., 2017a).

Food and nutrition insecurity are also urgent challenges for Guatemala and Honduras. The LAC region is facing the triple burden of malnutrition, which manifests in the simultaneous presence of malnutrition, micronutrient deficiency, and obesity (IICA, 2018). Since women are overrepresented among the rural poor in the LAC region (2/3 of the LAC population still lives in poverty), empowering women in agriculture would be key, not only for the sector's performance and for gender equality, but also for poverty reduction and FSN objectives (IDB, 2014; IICA, 2018). Rural women are more affected by food insecurity issues, but can play an important role in addressing it. Climate change is expected to exacerbate gender inequalities in terms of food and nutrition insecurity, and to increase the populations' overall vulnerability (Bryan et al., 2017a). In 2016, FAO calculated that in Guatemala, 1.5 million people need humanitarian assistance (915 000 are subject to food insecurity—severe and moderate— with 82 000 tons of maize lost) while in Honduras, 1.3 million people require humanitarian assistance (461 000 are food insecure – both severely and moderately, with 60% of maize lost) (FAO, 2016).

Both countries are also experiencing intensive processes of male migration, partly leading to a feminization of agriculture (IDB, 2014; Coello et al., 2015; IICA, 2018). In 2019, 20.6% and 34.2% of men in Guatemala and Honduras, respectively, had intentions of migrating compared to a 15% (Guatemala) and 31.8% (Honduras) migration of women (Quintana, 2019). This situation has important implications for the agricultural sector in terms of decision-making and production since, in the absence of men, the women must compensate by playing a greater role in agricultural production (Coello et al., 2015).

Data Collection

To examine gender mainstreaming in policy, we first established a general inventory of the main policy and regulatory documents (laws, frameworks, strategies, plans, and policies) related to each of the policy domains considered in our policy mix (i.e., agriculture, CC/ disaster risk management/ environment, FSN and gender) for each of the countries (**Table 1**) (see **Supplementary Material**). The three criteria used to select the policies were adapted from Drucza et al. (2020): (a) national policies specific to gender equality; (b) current national development plans; and (c) national policies related to agriculture, CC (risk management / environment), and FSN. The objective of this general overview was to establish a map of existing policies at the national level, as well as the international commitments to gender equality made by each country (and mentioned in their policy documents). By doing so, we gathered specific information on gender integration, at policy design level,

TABLE 1 | Sources of information for this study.

	Honduras	Guatemala
# Documents Document sector	23 policy and regulatory documents	28 policy and regulatory documents
	Agriculture, food security and nutrition, gender, climate change, risk management, environment (forest conservation)	Agriculture, food security and nutrition, gender, climate change, risk management, environment (forest conservation)
Documents type	Law, policy documents, program documents, National Development Plan, National Action Plan, National Strategy	Law, policy documents, National Communication on Climate Change, Strategic Plan, institutional strategy, Action Plan, program documents, National Development Plan
# Interviews	15 interviews	16 interviews
Date of interviews	Between October 2018 and May 2019	
Participating organizations	**Government**: National Women's Institute (INAM); Ministry of Agriculture and Livestock (SAG) (CC unit, gender unit and fishing directorate); Directorate of Agricultural Science and Technology (DICTA); Ministry of Environment; Technical Unit of Food and Nutritional Security (UTSAN) **ONU agency:** UNDP **NGO:** Red Cross, Action Aid (Ayuda en Accion) and Swisscontact **Civil society:** National Council of Cooperative Women (CONAMUCO), Women's Rights Center, Via Campesina	**Government**: Presidential Secretariat for Women (SEPREM); Ministry of Agriculture, Livestock and Food (MAGA) (Intercultural Rural Development Unit, gender unit, Planning Directorate); FONTIERRAS; Secretariat of Food and Nutritional Security (SESAN); Ministry of Environment and Natural Resources (MARN) **International Consultant** **University/Academics:** Universidad del Valle de Guatemala, ICEFI **Civil society:** The Foundation for the Development of Guatemala (Fundesa)

within the country's policy mix on gender, agriculture, CC, and FSN.

In addition to the policy document analysis, we conducted semi-structured interviews at national level with key informants such as governmental officials, international cooperation representatives, and civil society members (see **Table 1**). We identified the people to be interviewed using snowball sampling (Goodman, 1961) and from policy documents. All interviewees were working in agriculture, FSN, CC/ environment, and/or gender fields. The semi-structured interviews were conducted between October 2018 and May 2019 and focused on five components: (1) the characterization of the person interviewed; (2) the main gender issues in the country; (3) the level of gender integration into the policy cycle (design, budget, implementation, and evaluation) related to agriculture, CC, and FSN; (4) the drivers of gender integration problems; and (5) ideas to overcome the barriers to poor integration.

Data Analysis

The data analysis followed several steps. First, we analyzed the level of gender integration within the policy mix documents and in the countries' National Development Plan [based on Gumucio and Tafur (2015) grades] and the mention of international agreements related to gender. In addition, we searched for the existence of gender-labeled policy, programs or instruments in the policy mix (gender, agriculture, CC, and FSN). Finally, within the non-gender-labeled policy documents identified in the policy mix, we listed if they mentioned any international agreement on gender (sectorial and national level). This allowed us to assess gender inclusion in agenda setting and policy design.

Throughout the policy document analysis, we also examined the gender location in the institutional structure of our policy mix (gender, agriculture, CC, and FSN), which is an indicator of gender integration (True and Mintrom, 2001). This helped us to understand the way in which gender was integrated into the different institutions (through specific offices, in the different sectors). The key public institutions for each sector were identified, as well as the institutional platform/arenas for coordination among them through a stakeholder mapping.

To analyze the information shared during the interviews, we used a discourse analysis approach that is based "*on the assumption that reality is constructed through processes of social meaning-making, relying on the use of language as well as social practices*" (Leipold et al., 2019 p. 447). Specifically, we used policy narrative analysis methodology as developed by Béné et al. (2019), inspired by Roe (1994), on food systems issues, to identify and understand the different interpretations and narratives adopted by actors in relation to the integration of gender into policies on agriculture, CC, and FSN. More specifically, we examined the arguments of the key informants interviewed in response to the question: "To what extent is gender being mainstreamed in agriculture, CC, and FSN policy?." To do that, we identified the barriers to and solutions for gender equality within the policy cycle (Jann and Wegrich, 2007), namely: (1) agenda setting (corresponding here to international influence and national context); (2) policy design or formulation; (3) budget; (4) implementation; and (5) evaluation. Finally, the barriers and solutions were re-grouped, based on Giles et al. (2021) into four transversal categories: (1) international influence; (2) structural barriers at national level; (3) behavioral and corruption barriers; and (4) knowledge barriers. To do so, in an excel document, we grouped the barriers and solutions by categories and counted the barriers and solutions most mentioned by the interviewees. We compared the barriers and solutions between the two countries to identify similarities and differences. We also analyzed the types of actor (government, international cooperation, academic, private) mentioning more types of barriers and solutions. Finally, we compared solutions identified by the key informant interviews and the ones proposed in the gender policy documents.

RESULTS

This section first presents a brief contextualization of gender institutionalization within the governments of Guatemala and Honduras and then examines the level of gender integration within the defined policy mix, based on the policy documents' analysis. Following this, we present the main barriers to gender mainstreaming within the policy narratives reviewed, for the policy mix under consideration, comparing the two countries' barriers and the types of stakeholder barriers, considering gender integration across policy levels (from design to evaluation). Next, we present the solutions to improve the gender integration at different levels, identified through the stakeholders' narratives' and the policy documents' reviewed.

Gender-Oriented Institutional Structure of the Policy Mix: Gender, Agriculture, Climate Change, Food Security, and Nutrition

In order to provide an overview of the institutional context of Honduras and Guatemala, **Figures 1**, **2** present both countries' institutional layout concerning the policy mix of gender, agriculture, CC, and FSN domains. As reflected in these figures, both countries present a similar institutional setup with regard to gender, agriculture, CC, and FSN. In both countries, an overarching gender government body is located under the presidency (Presidential Secretariat for Women – SEPREM- in Guatemala and the National Women's Institute -INAM- in Honduras). Aside from this general gender-centered institution, there are also gender units located in sectorial ministries or secretariats. In the case of Guatemala, gender units are present at the presidency level under the Secretariat of Food and Nutritional Security (SESAN) and Secretariat of Planning and Programming (SEGEPLAN) and at the sectorial level in the Ministry of Environment (MARN), Ministry of Agriculture (MAGA), the National Forest Institute (INAB) and the National Land Fund (Fontierra) (see Here: **Figure 1**). In Honduras, there are also gender units located under the different directorates of the Secretariat of Agriculture and Livestock (SAG) such as the Directorate of Agricultural Science and Technology (DICTA), Directorate of Fishery (DIGIPESCA), and the Management Planning and Evaluation Unit (UPEG) (see here: **Figure 2**). In each municipality of Guatemala and Honduras, there is also either a gender office or directorate.

In both countries, the gender units are not considered as implementing bodies, which is reflected in the limited budget they are allocated. Often, these limited budgets are complemented by international cooperation funds through development projects. Furthermore, the gender units are made up of small teams (2 to 6 persons) who are supposed to cover a wide range of goals (e.g., raising awareness of gender issues among state officials, advising on gender integration, or gender policy implementation within entire ministries) in a wide territory of action (frequently at a national level).

In Guatemala, within MAGA there is the Unit for Intercultural Rural Development (UDRI), which is in charge of ethnic matters and is independent of the gender unit. In contrast, ethnic matters are integrated into the gender units in both MARN (Gender Equity and Multiculturalism Unit) and SEGEPLAN (Directorate of Ethnic and Gender Equity). In Honduras, the Secretariat of Social Works of the Wife of the President (SOSEP) and the Secretariat of Social Welfare (SBS) have some gender mandates and have government budget to implement projects. However, their actions on gender equality are very limited. As stressed by one of the interviewees, "SOSEP has done very little, very little in the way of gender. And, when it does, what it does is reaffirm roles... [...] It is the same as the SBS."

In general, gender governmental bodies are defined as weak, invisible, and with very limited capacity, resources, and political support (with some exceptions, such as the gender unit within MARN) (JICA, 2011 and key-informant interviews). This weakness was noted as especially noteworthy in the activities and project involvement of these gender units. For example, with regard to the specific tasks or projects that the gender units were involved with at the time the interviews were conducted, we found that in Honduras, the gender unit was not involved in any SAG project/program. Furthermore, some members of the gender unit were not working exclusively in the gender unit but also had other functions in parallel. For example, in DICTA, one person was in charge not only of the gender issues but also of rural credits and saving institutions ("cajas rurales").

In Guatemala, the gender units of institutions also presented a limited involvement in activities and programs, although the situation was somewhat more favorable than in Honduras. For example, MAGA's gender unit was participating in the ministry's flagship program for family farming and economic development, PAFFEC (Programa de Agricultura Familiar para el Fortalecimiento de la Economía Campesina), essentially working with unit directors to include gender considerations and women's participation on the one hand, and to document and share experiences on the other. In MARN, the gender unit had participated in the elaboration of the gender and CC strategy for the National Determined Contributions. Through the involvement and elaboration of these policy and strategic documents, the intention was to commit the members of the government and respective ministries to include gender considerations in their planning.

Gender Integration in the Guatemalan and Honduran Policy Mix and National Development Plans

In Guatemala, we found five main policies, that explicitly address gender equality and gender equity, in the scope of the studied policy mix (gender, agriculture, CC, and FSN): (1) the National Policy for the Advancement and Integral Development of Women (2008–2023); (2) the institutional policy for gender equality and strategic framework for implementation by MAGA (2014–2023); (3) the Gender Environmental Policy (2015–2020); (4) the institutional strategy for gender equity with ethnic and cultural relevance of Instituto Nacional de Bosques

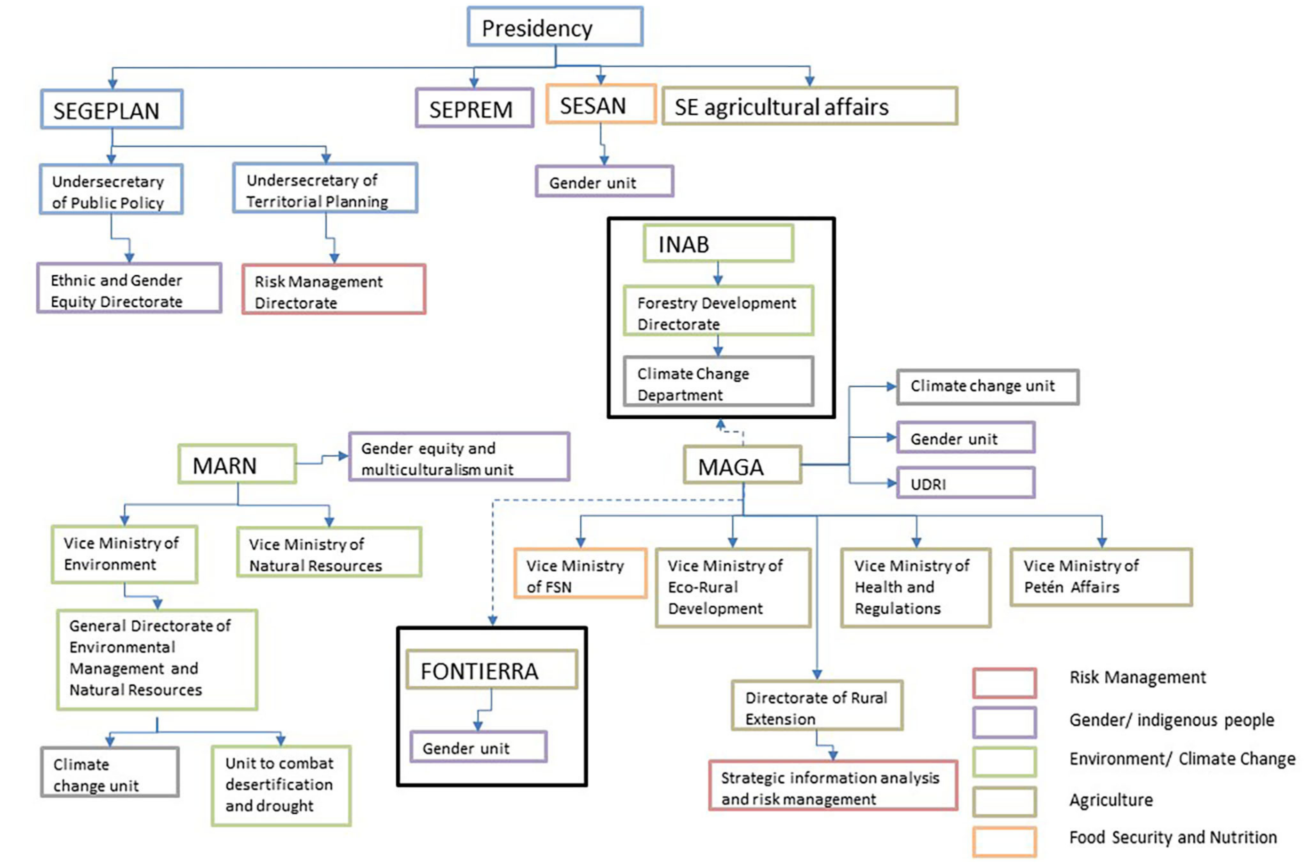

FIGURE 1 | Guatemalan government infrastructure on gender, agriculture, climate change, environment, risk management, and food security and nutrition (own elaboration).

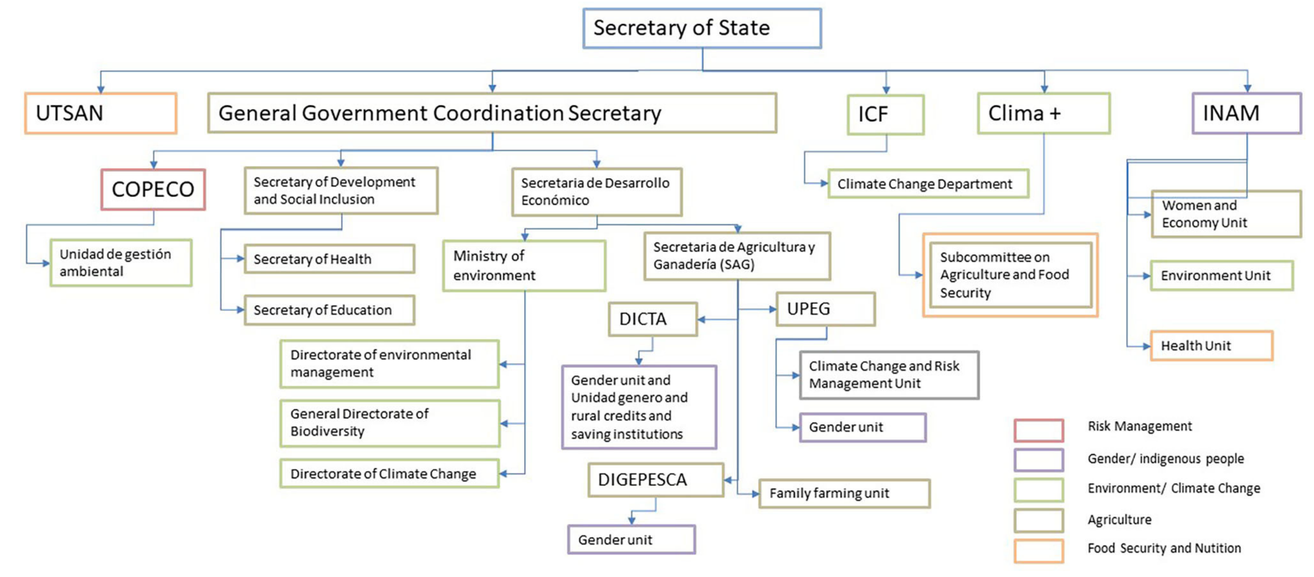

FIGURE 2 | Honduran government infrastructure on gender, agriculture, climate change, environment, risk management, and food security and nutrition (own elaboration).

(2013); and (5) the gender equality policy of the CONRED[1] Executive Secretariat (2016–2020). In Honduras, three main gender policies were found: (1) the Policy for Gender Equity in Honduran Agriculture (1999–2015); (2) the compendium of laws on women's rights and (3) the National Women's Policy (2010–2022). This corresponds to grade 4 of 5 grades in gender integration, according to Gumucio and Tafur (2015) ranking, i.e., *"Gender included in action plan, but absence of clear earmarked resources for implementation."*

There are thus not only national gender policies, but sectorial gender policies have also been elaborated for agriculture (Guatemala and Honduras), environment (Guatemala), forestry (Guatemala), and disaster risk management (Guatemala). In Guatemala and Honduras, no gender policy was found related to either food security and nutrition or climate change.

The Guatemalan National Development Plan (NDP) called "K'atun Nuestra Guatemala 2032' (2012–2032), makes explicit reference to six international agreements: the Millennium Development Goals (MDGs), the Post 2015 Agenda, the International Conference on Population and Development, the Women's Platform for Action, Rio +20, and the Hyogo Framework for Action. Those international agreements directly or indirectly integrate gender considerations, except for the Hyogo Framework for Action. Moreover, the Guatemalan NDP frames, as a sign of progress toward the Beijing Agreements, the promulgation of the National Gender Policy and its Action Plan; the creation of gender bodies; the development of a normative framework naming the CENADOJ (2008); the Decreto Ley N°9/2009 (2009); and the CONAPREVI (2008) (NDP 2012–2032, p. 71–72). Besides, the Guatemalan NDP includes strategic pillars related to well-being, wealth for all (specifying both men and women), natural resources, and human rights that can be related to gender issues. However, no mention is made to gender-related strategic pillar related to soils, agriculture or FSN.

In contrast, within the Honduran NDP 'Country Vision 2010–2018 and Nation Plan 2010–2022', gender is only mentioned on three occasions: (1) gender equity as a transversal strategic pillar for development objectives; (2) the crisis of representation based on ethnicity and gender that challenge democracy, citizenship and governance; and (3) within the vision for the goals of education, where it seeks to eliminate gender inequality.

Thus, in Guatemala and Honduras, gender is poorly integrated in the policy mix and NDP through few mentions (this corresponds to grade 2/5, according to Gumucio and Tafur (2015) ranking: "*Gender mentioned in overall objectives but absent from subsequent implementation levels*"). In **Table 2**, we summarize the main characteristics of gender integration at institutional layout and policy design level.

Table 2 indicates that there are no major barriers for gender integration in the policy mix of gender, agriculture, CC, and FSN at institutional and policy design levels.

TABLE 2 | Characteristics of gender integration within policy mix of gender, agriculture, CC and FSN and National Development plans in Guatemala and Honduras.

	Honduras	Guatemala
Policy domain where a gender-specific policy has been developed	Gender Agriculture - Grade 4 of gender integration (Gumucio and Tafur, 2015)	Gender Agriculture Environment Forestry Disaster Risk Management- Grade 4 of gender integration (Gumucio and Tafur, 2015)
Gender mentioned in National Development Plan	Yes (Country Vision 2010-2018 and Nation Plan 2010-2022')-Grade 2 of gender integration (Gumucio and Tafur, 2015)	Yes (K'atun Nuestra Guatemala 2032)–Grade 2 of gender integration (Gumucio and Tafur, 2015)
Coherence issues in policy objectives (tensions?)	Not visible	Not visible
Main instruments to deal with gender issue	National Women's Policy (2010–2022)	National Policy for the Advancement and Integral Development of Women (2008–2023)
Governance structure to assume integration	National Women's Institute (INAM) Gender units	Presidential Secretariat for Women (SEPREM) Gender units

Barriers to Effective Gender Mainstreaming

In this section, we present the most cited barriers to further integration of gender in Guatemalan and Honduran policies in both the reviewed policy documents and as mentioned in the key informant interviews. They are thematically organized into four sections: barriers relating to international influence, structural barriers at national level, behavioral and corruption barriers, and knowledge barriers.

Gender Barriers and Policy Translation From International Level

The inclusion of gender in policies, as well as its inclusion in the national political agenda, was framed and translated partly as driven by international cooperation in both Guatemala and Honduras, based on international concepts translated nationally. Interviewees related that through the combination of participation in international events, the signing of international agreements, and the influence/pressure/sensitization of international actors, and organizations, gender equality an equity issues had progressively become stronger in both countries. Partly as a result of this international cooperation, influence, and funding, gender policies and laws were elaborated, and gender bodies created. However, different interviewees highlighted that the government did not necessarily apply gender equality into policy, and that national actors did not fully embrace gender mainstreaming approaches, in their translation of gender into their policies. For example, an academic in Guatemala commented:

> "*Most people don't do it [include gender] because it's cool, but because there are indicators to be achieved and if not, the funds don't come. If you don't include this issue, if you don't have the strategies included, then there is no funding.*"

[1]CONRED: National Coordinator for Disaster Reduction.

Interviewees also highlighted the lack of coordination among international actors and their "top-down" approach that created a gap between the international cooperation lines of action and national realities, limiting the (gender) impact of interventions and questioning national autonomy. For example, three academics from Guatemala and three civil society informants from Honduras expressed frustration at the lack of positioning of international cooperation in relation to government decisions. Indeed, support for international cooperation has been mainly at the technical level (i.e., the development of policy documents) rather than at the advocacy level (debating the country's decisions and approach to development). In Guatemala, interviewees commented that the current context limits the advocacy efforts made by international cooperation actors. In Guatemala, there is a tense relationship between the government and the International Commission against Impunity, and the international cooperation actors, in general. An Academic commented: "*So I think that now the role of the United Nations, at least this year, is in a low profile.*"

Three academics in Guatemala also raised concerns regarding the Guatemalan law on "Non-Governmental Organizations for Development" (Ley de Organizaciones No Gubernamentales para el Desarrollo). The law allows greater state control over NGO finances, and allows the government to intervene and dissolve the NGOs, among other powers. The academics interviewed qualified the law as a 'censorship of national and international NGOs':

> "*Practically everything is going to be a crime, everything the NGOs do; if they protest and denounce, etc. It's like taking away the voice of civil society.*"

In Honduras, there were also concerns that the support from international cooperation to the government prejudices the civil society that fights for women's rights. A key informant from the Honduran civil society commented:

> "*In the last 4 years, we have had an administrative persecution with high levels of control over the organizations by the State, and the international cooperation has said nothing. (...) Cooperation [actors] (...) are afraid of being expelled.*"

According to the interviewees, in Honduras the financial resources from international cooperation were used to implement politicized interventions that had little effect on alleviating poverty or closing the gender inequality gap. For example, a civil society member in Honduras shared that the international cooperation did not question the Honduran government's neoliberal/extractive development model:

> "*Cooperation is not betting on another type of model that changes people's lives, but rather it is a cooperation embedded in the neoliberal capitalist model that is playing the same interests of the large transnational corporations. (...) I believe that it is necessary to investigate more exhaustively where the resources of cooperation come from, because there are those who may be making the rules.*"

Overall, in both countries, the influence of international cooperation was presented as having played an important role for the formulation of gender policies and strategies, but was also largely criticized for the top-down approach, and lack of coordination and advocacy actions that led to poor appropriation of gender in governments.

Structural Barriers at National Level

In both countries, two types of structural barriers were identified at rural women's and governmental levels. Interviewees remarked that the structural poverty in which rural women find themselves constitutes a key barrier to women's empowerment. Rural women face multiple sources of poverty and discrimination (less access to education, victims of stereotyping and violence, and exclusion from decision making), which limit their political participation and access to opportunities. For example, the double workload that women have and the lack of state infrastructure (e.g., kinder gardens) complicates their participation in development projects. There is also widespread violence against women and an intrinsic vulnerability due to the fact that women are not being sufficiently considered by the government. Women are not amply recognized in the agricultural sector; their role is often stigmatized and largely limited to supporting their husbands and to cultivating small-scale crops for home consumption. For instance, interviewees highlighted that in MAGA's projects and activities, women are largely not recognized as farmers, but rather as supporting male farmers. In Honduras, key informants shared that, historically, women have been forgotten/ignored in agricultural policies and are poorly active when involved in projects; several interviewees stressed the lack of land ownership by women as one of the main obstacles to women's empowerment in the agricultural sector.

Furthermore, the interviewees stated that in both countries, the extractive and neoliberal development model pursued by the governments go against smallholder farmers in general and rural women in particular, while favoring foreign multinationals and large landowners. This model was perceived as incompatible (or in conflict) with gender equity and FSN.

Another barrier highlighted in both countries was the weakness of gender institutions, which results in limiting the effectiveness of gender mainstreaming. The units are small, with few resources and little political support. In both countries, the lack of women in political positions of power limits the inclusion of gender in policies. This, added to the lack of articulation between governmental and international actors, and among international actors, and both national and local-level actors have been seen as limiting the impact of actions on behalf of women.

The gap between policy design and implementation is another barrier identified in the two countries. This particularly applies to the gap in gender policies. In Guatemala, interviewees explained there are many policies in place for which there is limited national budget, therefore gender policies are not a priority in budget execution, which partly reflects a lack of interest in gender equality issues by decision-makers. In Honduras, informants lamented the lack of a mechanism for monitoring and sanctioning the non-implementation of gender policies. In addition, the annual budget system in both countries limits the implementation of policy in the long term, with gender related actions being often eliminated from the budget. The interviewees also considered the lack of state policy as hindering the achievement of policy goals and making gender mainstreaming a decision of the administration in office.

Additionally, interviewees highlighted that the fact that gender is a crosscutting issue in both countries implies that no one takes ownership of the issue. Government officers do not have a crosscutting vision in their work. In Guatemala, an informant shared: "*When it belongs to all, it belongs to none.*" For example, Guatemalan extension workers consider that disaggregating data is not part of their work or that it is an extra workload and a subject outside their daily activities.

Behavioral and Corruption Barriers

Several interviewees remarked that civil servants (at the national and local level) have no interest in including gender in policy nor in recognizing the diversity of the population and its needs to be addressed. There is no interest from government decision-makers in reducing the budget gap either. The Guatemalan flagship program PAFFEC does not explicitly and intentionally integrate climate change, food security and nutrition, and gender, but it does so by accident, according to interviewees. In Honduras, as mentioned before, no SAG program includes gender.

Some interviewees went further claiming that corruption through groups of powers (military elites, the church, corrupt officials) is a way of functioning in the governments. It leads to poverty in the countries and the instrumentalization of social programs. In the case of Guatemala, the failure to integrate gender into the budget can be seen as a problem of priorities that no longer represent the realities of the country but, in reality, reflects the level of corruption in the country. There is an inertia in the distribution of the national budget where issues of national defense are more of a priority than social issues (such as gender equality). In Honduras, the breaking point that worsened the situation was the 2009 coup d'etat, while in Guatemala the breaking point was the expulsion by the President of the Republic of the International Commission against Impunity in Guatemala (CICIG) in 2018. In both cases, these events have deteriorated relations between the government and international actors, and civil society overall, and, in particular, those actors working on behalf of women.

Other interviewees described their countries as structurally (beyond the sphere of government) racist, sexist, violent, patriarchal, conservative, and religiously extremist, impeding the advancement of the inclusion of gender in policies. According to a Guatemalan interviewee, civil servants (mostly men) do not separate their personal views (racist, sexist, chauvinist, conservative…) from their public function. As such, gender integration competes with personal interests. The vision of how to resolve the gender gap responds to the assistance-based logic and unfounded victimization of women. In Guatemala, an interviewee explained that the gender equality and the feminist movement are discredited and delegitimized, often referred to as "feminazis" and thought of as turning people into homosexuals.

Knowledge Barriers

In Guatemala and Honduras interviewees considered that there is a lack of data, information, and diagnosis on the gender gap in agriculture and/or on the actions that have an impact on it. According to some of the Guatemalan actors interviewed, this is partly linked to the limited governmental monitoring and evaluation efforts that is partial and done on an *ad hoc* basis, often completed by international cooperation organizations.

For others, the lack of gender integration in policies is a problem of sensitization as is training of civil servants (at national and local levels) on gender issues. There is also a reported lack of capacity on how to conduct gender inclusion. Key informants in both countries pointed out the high rotation of government staff and the inadequate hiring of persons as additional barriers to achieving awareness and an open dialogue with international cooperation bodies or civil society toward gender issues.

When it comes to climate change, in both countries, interviewees revealed that climate change issues are addressed through a technical approach that excludes gender or social considerations. The urgency to act in the face of a disaster (in a risk management approach) in the Honduran dry corridor limits, for instance, the integration of gender in policy. According to a Honduran informant, there is more inclusion of gender in food security and nutrition policies than in climate change because of the roles socially attributed to women.

Finally, some interviews highlighted that the knowledge barrier is also due to the distinct understandings and definition of what gender mainstreaming is or involves (e.g., participation in activities vs. women's empowerment). Because of the lack of understanding of what gender integration means (limited to such things as women's participation in workshop, for instance), programs do not address the key issues that would close the gender gaps and improve food security and nutrition indicators. Examples of key issues would be: improve women's access to land, their participation in household decision-making, reduce their workload etc. In the case of Guatemala, programs currently often go against women's empowerment by promoting and reinforcing traditional roles for women. According to a Honduran informant, monitoring and evaluation (M&E) efforts should include more indicators than simply the number of women participating in activities.

In **Table 3** we present a summary of mentioned barriers for effective gender mainstreaming, by country. The ones in bold are the most mentioned by the interviewees.

Solutions for Effective Gender Mainstreaming

To overcome these barriers, interviews and policy documents have both provided solutions. In this section, we present the most mentioned solutions for greater integration of gender in Honduras and Guatemala according to where they were identified: actors' narratives or policy documents.

Solutions Found in the Narratives

The most mentioned solutions in the Guatemalan narratives were: (i) there is no short-term solution/ change will be difficult and long to achieve (six informants); (ii) the need to produce evidence on gender for political change (advocacy

TABLE 3 | Synthesis table of most mentioned barriers for gender mainstreaming in Guatemalan and Honduras policies.

	Narrative barriers	Guatemala	Honduras
International influence	Without international cooperation, there would be no progress in gender mainstreaming. The advances in gender inclusion have been made possible by international commitments and pressure that commit the country more than from real interest.	8	9
	There is a lack of articulation among international actors. Their "top-down" approach creates a gap between the international cooperation lines of action and national realities, which limit the (gender) impact of interventions and question national autonomy.	5	0
	International cooperation actors lack positioning with regard to government decisions. They blindly support governments.	3	4
Structural barriers at national level	**The structural poverty in which rural women are found constitute a key barrier to women's empowerment. Women are not recognized in the agricultural sector.**	8	**13**
	The extractive and neoliberal development model pursued by the governments goes against smallholders in general and rural women in particular, while favoring foreign multinationals and large landowners.	6	4
	The weakness of gender institutions limits gender mainstreaming.	8	**11**
	The gap between policymaking and implementation is a barrier identified for gender mainstreaming in policies.	**11**	**10**
	The lack of state policy is hindering the achievement of policy goals and makes gender mainstreaming a decision of the administration in office	8	8
	The lack of articulation between governmental and international actors and among international actors, both at national and local level is a barrier.	4	4
	Gender being a crosscutting issue, no one takes ownership of the issue: "When it belongs to all, it belongs to none."	**10**	4
	The annual budget system limits the implementation of policy in the long term. Gender-related actions are often eliminated from the budget.	8	8
Behavioral/Corruption	Civil servants (at national and local level) have no interest in including gender in policy nor in recognizing the diversity of the population and its needs to be addressed.	2	6
	Corruption through groups of powers (military elites, church, corrupt officials) is a way of functioning in the governments. It leads to poverty in the country, and the instrumentalization of social programs.	6	3
	The countries are structurally (beyond the sphere of government) racist, sexist, violent, patriarchal, conservative, and religiously extremist, which impede advances in the inclusion of gender in policies.	**12**	4
Knowledge/Capacity	There is a lack of data, information, and diagnosis on the gender gap and on actions that have an impact on it.	8	4
	The lack of gender integration in policies is a problem of sensitization, as is lack of training of civil servants (at national and local level).	**9**	**10**
	When it comes specifically to climate change, the issue is addressed through technical approaches that exclude gender or social considerations.	8	2
	There are distinct understandings and definitions of what gender mainstreaming is (participation in activities vs. empowerment).	4	5

The barriers in bold are those that were mentioned the most (by informants from Honduras, Guatemala, or both).

based on evidence) (six informants); (iii) implement training, sensitization, education at institutional/ population levels (six informants); and (iv) the development of state policies (five informants). In Honduras, the solutions that achieved the most consensus were: (i) strengthening the legal framework that protects women and/or enforce the law (nine informants); (ii) improving the design of programs to include women and/or see the impact on women (nine informants); (iii) improving financial support to civil society and gender units (nine informants); and (iv) training, sensitization, and education at the institutional and population level (seven informants).

In Guatemala, the interviewed academics agreed on the need to produce scientific evidence as a solution (five informants), a response that reflects their field of expertise. They did not see the strengthening of governmental gender entities as a strategic solution. On the other hand, civil servants working on gender issues saw education and sensitization as the main solution (four informants), and to a lesser extent the strengthening of government gender entities (two informants). Civil servants who do not work on gender issues saw solutions in promoting women's participation as citizens in society and seeking to achieve women's empowerment rather than participation in programs.

In Honduras, the civil servants working on gender issues focused more on strengthening and politically supporting government gender institutions and improving financial support in an articulated manner to foster program sustainability. At the civil society level, informants highlighted the need to strengthen civil society and its role in policy advocacy. Members of civil society and the international cooperation actors stressed the importance of the international cooperation promoting other models of development, as well as the need to address the structural poverty barrier (land ownership). The international cooperation actors cited the solution of producing evidence to support policy change.

Solutions Emerging From Policy Documents

The solutions identified in the policy documents of both countries were consistent with the actors' narratives and focused on issues such as the need to develop research actions to improve knowledge on the gender issues present, capacity building of civil servants on gender, strengthening the enforcement of gender-related legislation, improvement of financial support for gender units, and sensitization of the population on gender (see **Table 4**). Solutions to access to property (in MAGA's, MARN's and SAG's gender policies and, Guatemala's and Honduran's national gender policies) is also consistent with the interviewees' narratives (see **Table 4**).

It should also be noted that two documents mentioned the need for creating policies and programs that reduce the impact of macroeconomic policies on women's lives, which is also consistent with barriers identified by the interviewees in Guatemala and Honduras (see **Table 4**).

The documents also made frequent mention to issues of violence, racism, and discrimination, which was also consistent with the barrier on the structural issue of racism, sexism, violence, patriarchy, conservatism, and religious extremism highlighted by the interviewees in Guatemala and Honduras.

The document analysis also revealed that there seemed to be more focus on women's participation in interventions (in seven documents) than on women's empowerment (in three documents). This suggests that the gender community participating in policy elaboration has a distinct understanding and definition of what gender mainstreaming is (see **Table 4**).

Finally, policy documents made no mention of corruption issues, the lack of articulation among actors, or the low appropriation of gender as a cross-cutting topic. **Table 3** presents the solutions gathered to address gender inequality.

DISCUSSION

In this study we assessed the integration of gender in the policy mix, including gender, agriculture, CC and FSN policy using Guatemala and Honduras as case studies, and examined the barriers to and solutions for improved mainstreaming in those policies. The study constitutes an important contribution to the Central America policy analysis literature, confirming previous findings and also sharing new ones. In this section, we discuss our results in the light of the existing literature.

On the Role of Policy Translation From International Cooperation and Gender Integration in Policy Documents

Our study identified the relevance of the international context, through the mobilization of the policy translation concept, toward understanding the level of gender integration in policy, echoing the findings of other authors examining these issues (True and Mintrom, 2001; Rees, 2005; JICA, 2011; Kennett and Lendvai, 2014; Gumucio and Tafur, 2015; Mukhopadhyay, 2016; Acosta et al., 2020). United Nations (1996) constituted the symbol, and turning point, of the promotion of gender mainstreaming in policies, a practice that was adopted widely by governments, and which allowed both the elaboration, through translation of gender concept, of national gender policies and the creation of governmental gender entities (True and Mintrom, 2001; Kennett and Lendvai, 2014; Acosta et al., 2020). Besides influencing governments to include gender considerations in policy, our study supports recent study findings highlighting the important role of international cooperation for funding gender actions, which were otherwise unbudgeted through national mechanisms (Elson, 1998; IICA, 2015; Bryan et al., 2016; Njuki et al., 2016; Ampaire et al., 2020).

However, Guatemalan and Honduran interviewees and authors all agreed on the lack of impact of international cooperation actions. As other authors have pointed out, this mismatch is reflected in the gap that exists between international narratives and the production of documents on the one hand, and implementation and impact on the other (Bryan et al., 2016; Ampaire et al., 2020) and the lack of enforcement of the law in applying gender-sensitive policies (IICA, 2015; Ampaire et al., 2017), leading to an insufficient policy translation of mainstreaming efforts into progress in the area of gender equality (IICA, 2018; Acosta et al., 2020) and incomplete implementation of an effective policy integration.

Our study found a context of poor relationship between the government and the international cooperation conducted in Guatemala, and the disengagement of international cooperation actors, both of which were seen as barriers to influencing policy, and neither of which were reported elsewhere in the literature examined. The narrative on the bad relations between international cooperation and the government was included in an ICEFI Bulletin on the analysis of the public budget for 2018 (Bulletin 24, ICEFI, 2018), but did not link it to the gender issues in the country.

Similarly, in Honduras, our study reveals how some informants highlighted the problem of international cooperation support for the government, which is characterized by its persecution of civil society that fights for women's rights. The issue of the lack of positioning regarding the government's development model and the politicization of public resources and the international cooperation, and the issue of national autonomy being put at risk by international cooperation was not reflected in the literature.

As shown in this study, although gender is integrated in sectorial and national policy, it is not sufficient to observe a change in bridging/closing the gender gaps (no gender

TABLE 4 | Lines of action to support women's mainstreaming in gender policy documents.

	INAB (G)	MAGA (G)	National (G)	MARN (G)	CONRED (G)	National (H)	SAG (H)	law compendium (H)	Total
Strengthen internal capacities in gender	1	1		1	1	1	1		**6**
Guaranty men's and women's participation in interventions/ in policy	1	1	1	1	1	1	1		**7**
Create gender sensitive indicators/ MandE system		1	1	1	1	1	1		**6**
Empower (rural) women		1			1	1			**3**
Create policies and programs that reduce the impact of macroeconomic policies on women's lives			1			1			**2**
Lead research on gender issues		1	1	1		1			**4**
Foster women access to property/ Establish land titling policies		1	1			1	1		**4**
Establish specific gender attention in case of disaster/ gender focus on disaster management			1	1	1	1	1		**5**
Sensitize population on gender issues (participation/ violence/ discrimination, racism)			1	1	1	1	1		**5**
Have a special focus on rural women in poverty, in terms of food and nutritional assistance and community food production/ focus on gender and FSN		1	1	1		1	1		**5**
Include special focus on women in REDD+/ CC interventions			1	1		1			**3**
Enforce gender laws (violence/ racism/ discrimination)/ enforce implementation of gender policies			1	1		1		1	**4**
Strengthen gender institutions (politically and financially)	1	1	1	1	1	1			**6**
Include gender in sectoral policies/projects/programmes/documents	1	1	1	1	1	1	1		**7**
Create budget for gender policy implementation/ gender sensitive budget		1	1	1	1	1			**5**

integration in policy implementation and evaluation). In stark contrast to the case of Ethiopia (Drucza et al., 2020), Guatemalan and Honduran policy is aligned with international conventions at policy design level, but implementation is lagging. Besides, housing national and sectorial gender policies within specific gender units seems to disembody gender as a cross-cutting topic, and reduces ownership of the topic for non-gender civil servants in other units.

On the National Context

Both the narratives found in the literature (Bryan et al., 2016; Acosta et al., 2020; Ampaire et al., 2020) and the country cases confirm the gap between the creation of policies and their implementation. In this regard, Gumucio and Tafur (2015) assess the degree of gender integration in CC and FSN policies using five grade categories, from grade 1 (no reference to gender issues) through to grade five (gender included in the document from objective to action plan with resources for implementation). Gumucio and Tafur (2015) results showed that, the majority of policies reviewed by our study have been rated with grade 2. The temporal analysis of the policy documents reveals an incremental emergence of gender considerations. but that remain general and unspecific (Acosta et al., 2019b). This situation is explained in the Guatemalan case by a lack of real interest of government actors in integrating gender into policies (beyond its inclusion in documents), a point also mentioned by Bryan et al. (2016). Similarly, the lack of enforcement of the existing law or measures to enforce it was reported among both Honduran and Guatemalan informants and in the literature (JICA, 2011; Ampaire et al., 2017). In this way, the implementation of gender mandates is not considered compulsory but optional. These findings are important from two perspectives: on the one hand, they allow the deep analysis of the level of integration of gender within policy documents; on the other, they allow going beyond the mere analysis of the document to assess the level of implementation and evaluation of such policies.

The narrative found both in the Guatemalan and Honduran cases and in the literature, postulates that the lack of gender integration comes from the way governments operate, divided by sectors and not used to working on cross-cutting issues (as promoted at international level). Because of its cross-cutting nature, gender is seen as an extra workload. This resonates with the literature, which points out the lack of awareness on gender issues (IICA, 2015), a lack of acceptance of the inclusion of gender by members of government (Ampaire et al., 2020), partly because it is perceived as causing extra workload (Bryan et al., 2018) and a lack of information in general about what the gender gap represents (Bryan et al., 2016, 2018; Njuki et al., 2016). This narrative also underscores the lack of coordination among government members due to the fact that the government operates in silos (Ampaire et al., 2017) and the problem of including 'new issues' that cut across traditional sectors such as the Ministry of Agriculture (Levy, 1992). The study on policy mix for sustainable transitions conducted by Rogge and Reichardt (2016) highlighted the key role of coordinating structures and communication networks toward achieving coherence among policy instruments of distinct policy domains and also achieving the overarching goal of a policy mix (performance of the policy mix). For these authors, one of the major tools needed to achieve policy coherence is policy integration "*by enabling a more holistic thinking across different policy sectors, at the same time involving more holistic processes*" (Rogge and Reichardt, 2016 p. 1627).

The narrative in which a link is established between the country's structural poverty and the lack of gender integration in policies was found in the narratives mentioned by the interviewees in both countries and in the literature on the region. In fact, Oxfam (2015) establishes a relationship between inequalities in the distribution of land in this region, due to pressure from large landowners and the agricultural development model based on extensive crops, which affects small-scale producers and even more so women producers. Thus, it is the entire economic and social system that is questioned in this narrative. Mayoux (1993) argues that social and agricultural policies do not propose solutions that challenge structural gender inequalities and will therefore not overcome them. This finding is also related to the Honduran narrative in which the extractive and neoliberal model pursued by the Honduran government harms male and female farmers while favoring foreign multinationals and landowners. Public policy does not seek transformational change to address the challenges of the effects of CC, but rather serves the interests of extractive projects.

The Guatemalan narrative about the non-use of the M&E system, its data limitations and difficulty in accessing data, corresponds to the narratives in the literature that indicate: (1) a lack information, understanding, and research on gender (Daly, 2005; IICA, 2015; Bryan et al., 2016, 2018; Njuki et al., 2016; Ampaire et al., 2020) and (2) there is a lack of capacity on gender issues (IICA, 2015; Bryan et al., 2016; Njuki et al., 2016; Ampaire et al., 2020).

There is also consensus among Honduran and Guatemalan informants and the literature (JICA, 2011; IICA, 2015; Bryan et al., 2016; Njuki et al., 2016; Ampaire et al., 2020) on the weakness of the gender institutional framework in terms of human resources staff capacity. For example, in Honduras, women's offices are being closed due to lack of resources (JICA, 2011). As JICA (2011 p. 20) concludes: "*The needs and interests of women are not central to the analysis and strategies of poverty reduction, and women remain on the margins of the poverty reduction process*". In terms of women's participation in politics, studies confirm the marginal space occupied by women, with 19.5% of them in the National Congress between 2010 and 2014 (JICA, 2011). Furthermore, at the local level, the proportion of women mayors is below 10% (JICA, 2011).

The study found no comments on the process of silencing and censorship of civil society by State law in the literature.

On Behavior and Corruption

There is a consensus between interviewees and literature findings indicating state corruption, patriarchal culture, and lack of interest by politicians as three constraints affecting the effectiveness of gender mainstreaming. In the literature, a lack of interest has been shown to be a barrier (Bryan et al., 2016; Mukhopadhyay, 2016). Corruption as a mode of functioning and orchestrated by power groups that favors poverty and inequality has also been contemplated in the literature, as has patriarchal culture (Mayoux, 1993; Njuki et al., 2016). This idea is also developed in an Oxfam report (2015) that speaks of the "hijacking of democracy" that translates into corrupt practices by the economic and political elites, giving as examples clientelism, vote buying, the hiring of public employees because of their political affiliation, the prioritization of assistance policies, the granting of public services as favors, and the influence on the media (among others). The influence of religion in policy that tends to maintain traditional gender roles is also an aspect identified both in the case studies and in literature (Drucza et al., 2020).

Finally, the last three narratives constitute a gradient of the same narrative. Indeed, Bryan et al. (2017b) emphasized the complexity of the policy design process that translates into negotiations among actors, their own needs, and preferences and priorities, which sometimes has negative effects on policy outcomes. These potential tensions and disagreements among policymakers are observed not only at the national level, but also at the local level (Acosta et al., 2020).

On Awareness, Knowledge and Capacity to Address Gender Issues

The narratives for Honduras and Guatemala, and elsewhere in the literature, coincide in identifying knowledge and capacity barriers acting as a brake on gender mainstreaming (IICA, 2015; Bryan et al., 2018; Ampaire et al., 2020). This lack of gender awareness also translates into the co-existence of different definitions of gender equality and gender mainstreaming in policies and therefore different understandings of how to achieve it (Walby, 2005; Acosta et al., 2020). Indeed, gender norms formulated and defined at the international level may compete with other informal norms at the local level (Acosta et al., 2019a) or be oversimplified through multiple translation processes (Kennett and Lendvai, 2014). The lack of capacity among public servants on gender issues identified in Honduras and in the literature reinforces this barrier (Bryan et al., 2016; Ampaire et al., 2017).

In the specific case of CC, the lack of gender inclusion is explained by the technical approach given to this issue ignoring its social aspects (Gumucio and Tafur, 2015; Mukhopadhyay, 2016; Njuki et al., 2016; CDKN, 2017; Acosta et al., 2019a). The case of CC is illustrative since it is an issue that is largely politicized at the international level by actors such as the Intergovernmental Panel on Climate Change (IPCC), the scientific advisory body of the United Nations Framework Convention on Climate Change (UNFCCC), the United Nations Environment Programme (UNEP) and the World Meteorological Organization (WMO), all of which delayed integrating the discussion on the gender dimensions of climate change, focusing, at first, to a greater extent on technical aspects and solutions to CC (Resurreccion, 2011). Fordham (2003) speaks of the "*tyranny of urgency,*" taking up an expression from BRIDGE (1996) according to which the urgency of a situation allows the elimination of gender (or social issues, in general) through prioritization.

On Solutions

In the literature, solutions or recommendations are promoted to improve gender integration in policy. Eight main types of solutions have been identified: (1) to promote participatory mechanisms and multi-stakeholder collaborations during the policy-making process (FAO, 2011; Gumucio and Tafur, 2015; Huyer et al., 2015; Tafur et al., 2015; Bryan et al., 2016; Ampaire et al., 2017; Dinesh et al., 2018); (2) to lead capacity building and strategic communication actions at all levels (Ampaire et al., 2017; Dinesh et al., 2018); (3) to include gender considerations at all stages of project cycles (including budget for M&E) (Gumucio and Tafur, 2015; Huyer et al., 2015; Tafur et al., 2015; Ampaire et al., 2020); (4) to establish or adjust policy objectives so that they go beyond improving women's participation (Huyer et al., 2015; UNDP, 2016; IICA, 2018); (5) to use legal instruments as motivation and guidance for gender integration (Gumucio and Tafur, 2015; Tafur et al., 2015; Ampaire et al., 2017; IICA, 2018); (6) to lead more research on gender to inform policy and project design (Huyer et al., 2015; Bryan et al., 2016, 2017b; Dinesh et al., 2018); (7) to improve policy implementation at local level through a more effective decentralization (Ampaire et al., 2017); and (8) to improve gender-sensitive M&E, integrating sex-disaggregated data and a mix of quantitative and qualitative analysis (DANIDA, 2006; World Bank, 2012; Tafur et al., 2015; Njuki et al., 2016; UNDP, 2016; Bryan et al., 2018).

Some of the solutions mentioned by interviewees in both countries and in policy documents are consistent with literature findings such as the need to keep building capacity on gender, to produce scientific evidence on gender to inform policy, to push for more law enforcement, to foster women access to property, and to improve policy and project design.

Nevertheless, in literature we found no mention of the level of discouragement and feelings of powerlessness of key informants on the situation they shared, to which they saw no solution, as was particularly the case in Guatemala. Furthermore, there were no references to the need to strengthen sectorial gender units and civil society (both financially and in terms of capacity).

Neither in this study (interviews and policy documents) nor in the literature were concrete solutions proposed to overcoming the barriers related to structural racism and machismo, religious extremism, power groups, and censorship of civil society.

CONCLUSION

This study has pointed out the barriers limiting gender mainstreaming in agriculture, CC, and FSN policies, using the cases of Guatemala and Honduras. Relying on the concepts of policy integration (the object of our analysis, from policy design to evaluation), policy mix (that defined the scope of the study), and policy translation (that considers the translation of international standards in national level policy design), we first show that gender integration is currently occurring through the creation of a dedicated overarching administration and sectorial dedicated unit, and the inclusion of the gender issue in development and sectorial policy documents. Yet, the analysis of policy narratives in documents and stakeholder interviews also reveals the gender-mainstreaming obstacles permeating a variety of levels, from how international influence translates into national policy design, to behavioral and corruption-related, knowledge and capacity levels of civil servants. Nonetheless, our study also documented solutions to overcome the barriers identified that are related to research, capacity building and sensitization on gender issues, financial support, and women's access to property.

The study results for both Guatemala and Honduras showed similarities and differences in barriers and solutions.

Our case confirms results from the literature, such as the important role of international cooperation and treaties in influencing gender mainstreaming in the national context. But it recognizes it as an insufficient condition to achieve impact. Additionally, our study showed, the importance of considering the nature of the relationship (purely technical and/or political) between governments and international cooperation actors, in order to understand the level of gender mainstreaming in policy. At the national level, our study confirmed the literature in pointing to the gap between policymaking and policy implementation, the difficulty of integrating a transversal topic such as gender in sectorial ministries, the structural poverty of rural women, lack of monitoring and evaluation, and the weakness of the gender institutional framework. Our study points to an additional barrier of the contexts of silencing and censorship of civil society by State law. On behavior and corruption, our study was consistent with the literature, identifying issues of corruptions, patriarchal culture, and poor interest in gender issues. Barriers of knowledge and capacity at civil servant and population levels were also shared between our results and the literature findings. The technical approach given to climate change issues is a specificity that also constitutes a barrier to gender mainstreaming in this sector.

Solutions to overcome poor gender mainstreaming have been identified in the literature and through our study, such as the need to produce evidence at the local level on women's role and contribution in agriculture, FSN, adaptation to and mitigation of CC, but also on related gender gaps, implementing training and sensitization actions at national and local level for civil servants and the population, strengthening the legal framework on gender, improving financial support to civil society and gender units, to name but a few. Moreover, our results shed new light on the feelings of discouragement and powerlessness of key informants regarding women's situations in these countries. Finally, no immediate solutions were identified to overcome the particular barrier of structural racism and machismo, religious extremism, power groups, censorship of civil society permeating both countries.

DATA AVAILABILITY STATEMENT

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

ETHICS STATEMENT

Ethical review and approval was not required for the study on human participants in accordance with the local legislation and institutional requirements. Written informed consent for participation was not required for this study in accordance with the national legislation and the institutional requirements.

AUTHOR CONTRIBUTIONS

FH: led methodological design, data collection, data analysis, and led writing manuscript. MA, JM, and J-FL: contributed to methodological design, literature review, and contributed to the paper revisions. All authors contributed to the article and approved the submitted version.

FUNDING

This work was funded by the CGIAR Research Program on Climate Change, Agriculture and Food Security (CCAFS), which was carried out with support from CGIAR Fund Donors and through bilateral funding agreements. For details, please visit https://ccafs.cgiar.org/donors. The views and opinions expressed in this document are those of the authors and do not necessarily reflect official positions of the sponsoring organizations. CCAFS was led by the International Center for Tropical Agriculture (CIAT).

ACKNOWLEDGMENTS

We acknowledge the valuable contribution from the stakeholders that participated in the process, and we would like to thank them for their time, knowledge and patience. We finally acknowledge Olga Spellman (Alliance of Bioversity International and CIAT) for English and technical editing.

SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fsufs.2021.664253/full#supplementary-material

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Conflict of Interest: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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ORIGINAL RESEARCH
published: 07 June 2021
doi: 10.3389/fsufs.2021.677069

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Developing Climate Information Services for Aquaculture in Bangladesh: A Decision Framework for Managing Temperature and Rainfall Variability-Induced Risks

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OPEN ACCESS

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Specialty section:
This article was submitted to Climate-Smart Food Systems, a section of the journal Frontiers in Sustainable Food Systems

Received: *07 March 2021*
Accepted: *23 April 2021*
Published: *07 June 2021*

Citation:
Hossain PR, Amjath-Babu TS, Krupnik TJ, Braun M, Mohammed EY and Phillips M (2021) Developing Climate Information Services for Aquaculture in Bangladesh: A Decision Framework for Managing Temperature and Rainfall Variability-Induced Risks. Front. Sustain. Food Syst. 5:677069. doi: 10.3389/fsufs.2021.677069

Climate information services (CIS) are increasingly in demand to assist farmers in managing risks associated with climate variability and extremes experienced in food production. However, there are significant gaps in the availability and accessibility of these services, especially in aquatic food production in developing countries. In response, this study aims to generate the background knowledge for developing climate information and decision support services tailored for aquaculture farmers in Bangladesh. We surveyed 800 fish-farming households, interviewed 30 key informants, and conducted a systematic literature review to identify climate-sensitive operations and management decisions in aquaculture and to document fish-farmers' awareness of the relationships between climate variability and aquatic food production systems. We also sought to identify the lead time and communication method(s) needed to deploy forecasts effectively and prepare aquaculture farmers to act in response to the forecasts. A fish-farming activity calendar was developed that identified high temperature, cold spell, heavy rainfall, and dry spell events as key climatic phenomena affecting year-round aquaculture operations, including pond preparation and maintenance, fingerling stocking, grow-out management, and harvesting. We also identified five climate-sensitive management decision points and 26 potential advisories in line with specific climate variability to manage induced risks in the day-to-day operations of fish farmers. Finally, the research team developed a decision framework based on the temperature and rainfall thresholds for the grow-out phase of four widely cultivated and economically important fish species in Bangladesh. This innovative decision support approach is to our knowledge the very first endeavor to develop CIS using species-specific temperature and rainfall thresholds to reduce climate risks and ensure resilience capacity for South Asian aquaculture system.

Keywords: climate, variability, risks, aquaculture, services, threshold, fish-farmers

INTRODUCTION

Bangladesh is one of the most suitable countries for aquatic food production in the world, given its large inland freshwater (45,000 km^2) and marine water bodies (Ghose, 2014; Shamsuzzaman et al., 2017). It is ranked 3rd in inland fisheries, 5th in aquaculture, and 11th in marine fish production globally (Sarder, 2020). The prominence of aquatic food in the country is reflected in the diet (accounting for 60% of animal protein intake), livelihood opportunities (employing more than 10% of the country's population through fishing, aquaculture, handling, and processing), and economy (contributing about 5% to the country's GDP) (Belton et al., 2014; Bogard et al., 2015; BFTI, 2016; MoF, 2020). However, the sustainability of aquaculture and capture fisheries is increasingly challenged by climatic stresses. The country has been identified as the second most climatically vulnerable country in Asia for freshwater aquaculture and is marked as having the lowest adaptive capacity for brackish water production due to an expected increase in climate variability and frequency of extreme weather events due to global climate change (Barange et al., 2018). These climate stresses impact aquatic food production in multiple ways, such as high water temperatures exceeding the physiological tolerance level of fish species, sudden temperature fluctuations leading to fish mortality, and erratic or intense rainfall events causing harvest losses, which are among the challenges facing aquatic food production systems.

Bangladesh's monthly maximum temperatures remain generally higher (>34°C) in April, May, and June, while monthly minimum temperatures are lower (<20°C) in December, January, and February (Khatun et al., 2016). Besides, the number of extreme hot days, i.e., maximum temperature of >40°C, occurs during April and May. The number of days with maximum temperature ranging from 30 to 36°C per year varies between 109 and 175 days in different parts of the country. Conversely, suitable temperature for fish farming in Bangladesh ranges from 26 to 32°C (Roy et al., 2019). In addition to temperature stress, rainfall variability also exerts stress in aquatic food production. An increasing number of dry spells are recorded in February, April, May, August, and November, while extreme rainfall events are increasing in July, September, and October (Khatun et al., 2016; Hossain, 2018). Temperature (both maximum and minimum) and rainfall variability pose significant risks for aquatic farming activities and require modified management decisions to reduce the risks. Approximately 25% of loss and damage occurred in agriculture, fisheries, and aquaculture sector during the period of 2003–2013 in developing countries can be attributed to climate related impacts (Shelton, 2014). In Bangladesh, a single extreme weather event, such as cyclone "SIDR" caused damages worth USD 6.71 million in aquatic food systems by washing away fish, shrimp, and fingerlings and by damaging infrastructure, gears, and equipment (GoB, 2008). Similarly, a single flood event in 2020 caused USD 5 million worth of loss to the fish farms through infrastructural damage and washing away fishes and fingerlings (Saha, 2020). So, it is evident that climate variability and extreme climatic phenomena are significantly affecting the aquatic food production in Bangladesh.

With high-quality climate information and skillful forecasts tailored to the needs of the fisheries or aquaculture sectors, fish farmers could be empowered to adapt and manage stresses (WorldFish, 2020) and, hence, offset the climate impacts. There is a need for a deep understanding of the sensitivity of different aquaculture operations to specific climatic variables to ensure access to appropriate climate information services (CIS) enabling decision-makers to adapt their decisions. Identification of climate-sensitive aquaculture operations and portfolio-adaptive decisions are, therefore, prerequisite to the development of CIS for aquaculture.

Moreover, 194 countries signed the Paris Agreement for Nationally Determined Contributions (NDCs) in 2015 to transform their development trajectories through adaptation and mitigation efforts (Kalikoski et al., 2018). However, the NDC submissions did not specify mechanisms that could be deployed to support the most vulnerable and poor to deal with climate extremes. In particular, fisheries and aquaculture were inadequately considered. In response to these gaps, there is a considerable scope to integrate and mainstream CIS in national plans, policies, and strategies as a mechanism aiding in enhancing climate resilience. Many countries have begun implementing CIS for agriculture to address climatic risks (Dayamba et al., 2018; Vaughan et al., 2019; Cheng et al., 2020) and meet adaptation needs; however, the application of CIS is a newly emerging field in the aquaculture sector (WorldFish, 2020). Given the potential of CIS in offsetting climate risks to a significant extent (Hansen et al., 2019; Vaughan et al., 2019), it can potentially act as a mechanism to increase investments in aquaculture by small farmers.

Considering the extensive aquatic resources of Bangladesh, the climate impacts on aquaculture production, the socioeconomic vulnerability of small-scale fish producers, and the current lack of CIS for aquaculture in Bangladesh, this study aims to develop a timely, reliable, and contextualized decision support framework to assist small-scale fish farmers in managing climate risks. To develop this framework, we analyzed three tiers of information: field surveys, key informant interviews, and a literature review. We investigated aquaculture management information relevant to CIS, fish producers' knowledge on the effects of climate variability on different aquaculture operations, and their perceptions on the use of CIS. We then mapped out climate-sensitive aquaculture operations and management decisions for climatic variables (and their variability) that could benefit small-scale fish farmers. Finally, we identified temperature and rainfall thresholds for four widely cultivated and economically important fish species to formulate advisories for reducing associated risks.

MATERIALS AND METHODS

As part of the three-step investigative procedure, we first designed an aquaculture survey module (**Supplementary Material 1**). This module is based on a combination of field level observation (on fish-farming practices, daily management operations, current demand and access to

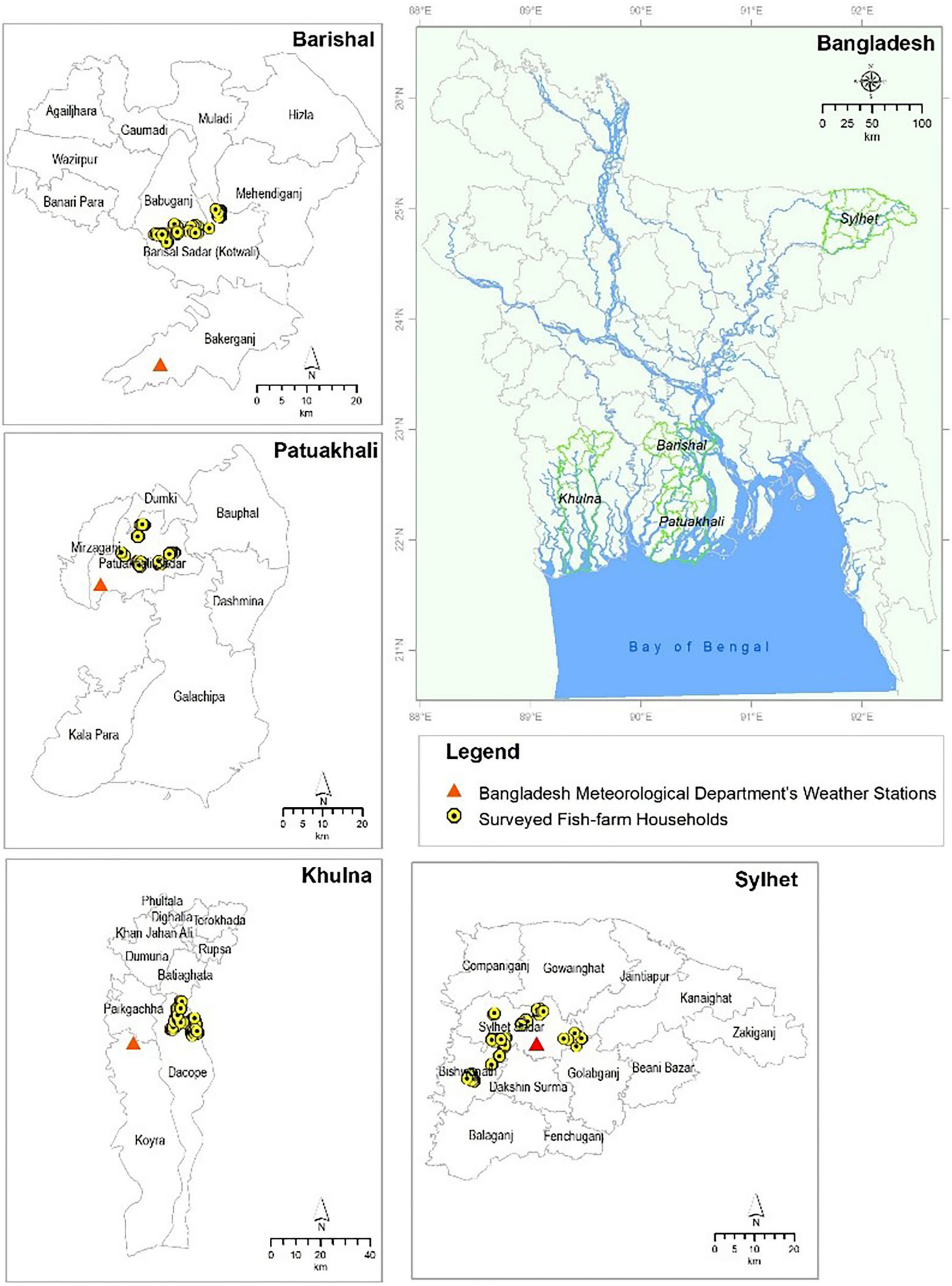

FIGURE 1 | Study sites.

TABLE 1 | Demographic status of fish-farming households of the four studied districts.

Category	Characteristic	Percentage of the respondents			
		Barisal	Patuakhali	Khulna	Sylhet
Gender	Male	97	98	93	95
	Female	3	2	8	5
Age	>18	68	67	76	64
	13–18	21	21	18	23
	<13	11	13	7	13
Marital status	Married	69	70	78	68
	Unmarried	31	30	22	32
Education	Illiterate	28	9	19	7
	Primary	41	54	39	44
	Secondary	23	27	25	33
	Higher secondary	8	10	12	8
	Graduate	0	0	5	9
Family type	Joint	70	65	78	46
	Nuclear	30	35	22	54
Family size	Small (≤5)	55	62	68	36
	Big (>5)	45	38	32	64

CIS) and desk study to collect a wide range of information from small-scale fish producers (such as demographics, species selection and management information, perceptions of climate impacts on aquaculture, and potential use of CIS). The aquaculture module was deployed in four districts (**Figure 1**) with aquaculture farming activities of small-scale fish farmers. Three districts (Khulna, Barisal, and Patuakhali) from the south-west coastal region and one district (Sylhet) from the north-east *haor* region were selected, the latter being a low-elevation, landscape with a saucer-shaped depression that hosts a wetland-based ecosystem. The districts were selected based on their contribution to cultured fish production in Bangladesh and their exposure to climate risks, particularly temperature and rainfall variability. Four upazilas (subdistricts) were selected from the chosen districts, within a 15- to 25-km radius of the Bangladesh Meteorological Department's (BMD) weather observational stations that provided data for this study. In total, 800 small-scale fish-farming households who are directly involved in fish-farming activities have been surveyed using stratified random sampling (Howell et al., 2020) from October 2019 to December 2019, which covered 18 unions (smallest administrative units) of the selected upazilas (**Supplementary Material 2**).

Next, we interviewed 30 key informants (selected based on their work experience and expertise relevant to climate impacts on aquaculture research and development) from various government and non-government organizations, universities, and research institutes, purposefully to gather information on the key weather scale impacts affecting aquaculture practices and climate-sensitive aquaculture operations. In addition, the aquaculture experts identified management decisions relevant to the identified climate-sensitive aquaculture operations, critical temperature and rainfall thresholds for widely cultured and economically important fish species in the region, and the expected outcomes from aquaculture CIS.

Lastly, we reviewed the available literature using the ISI-Web of Science, Google Scholar, and Google Search. The review focused on scientific validation of growth phase-specific conditions (temperature and rainfall thresholds) and potential adaptive decisions (to offset the impacts of adverse climatic conditions) identified from the interviews with aquaculture farmers and experts in order to develop useful climate advisories for the key economically important species in Bangladesh. Key search terms used were critical temperature, critical temperature thresholds, heat stress, thermal stress, high-temperature thresholds, low-temperature thresholds, cold spell, heavy rain thresholds, dry spell, drought, and low-rain thresholds. We also used the names of the fish species (both local and scientific) as search terms: rohu (*Labeo rohita*), tilapia (*Oreochromis nilotica*), black tiger shrimp (*Peneaus monodon*), and freshwater prawn (*Macrobrachium rosenbergii*). The resulting articles were first filtered reading the title followed by the abstract. Final scrutinizing considered the grow-out phase and thresholds (**Supplementary Material 3**), which we used to cross-check with the thresholds identified by the experts during the key informant interviews. As the literature review and key informant interviews produced only qualitative information on rainfall thresholds, like very heavy rain, heavy rain, low rain, or dry spell, we collected quantitative information on rainfall thresholds for heavy, very heavy, and low rain from BMD.

Using a systematic and logical combination of three sets of information (fish producers' response, expert opinion, and the literature review), we developed the aquaculture decision framework considering four widely cultured and economically important fish species sensitive to temperature and rainfall variabilities (**Appendix A**). The timeline considered for the decision framework is the grow-out phase of the selected fish species identified during the fish-farmer survey, which was also cross-checked during the key informant interviews. Climatic thresholds for the selected fish species were identified from expert opinion and the literature review considering the least standard deviation of the mean thresholds. The decision points were identified considering both the fish-farmers' and key informants' responses on climate-sensitive aquaculture operations for the grow-out phase of the selected species. Finally, the advisories were developed based on the list of climate-sensitive management decisions identified by the fish farmers as well as the key informants in line with specific decision points and climatic variables. Where thresholds were crossed, recommended actions were developed that could be supplied to fish farmers with the goal of reducing climate risks and enhancing the resilience of the small-scale fish farmers.

RESULTS

Demographics of the Fish Farmers and an Overview of Fish-Farming Practices

Almost all fish farmers (>90%) surveyed were male, and 50–70% were literate with primary (8 years) and secondary education

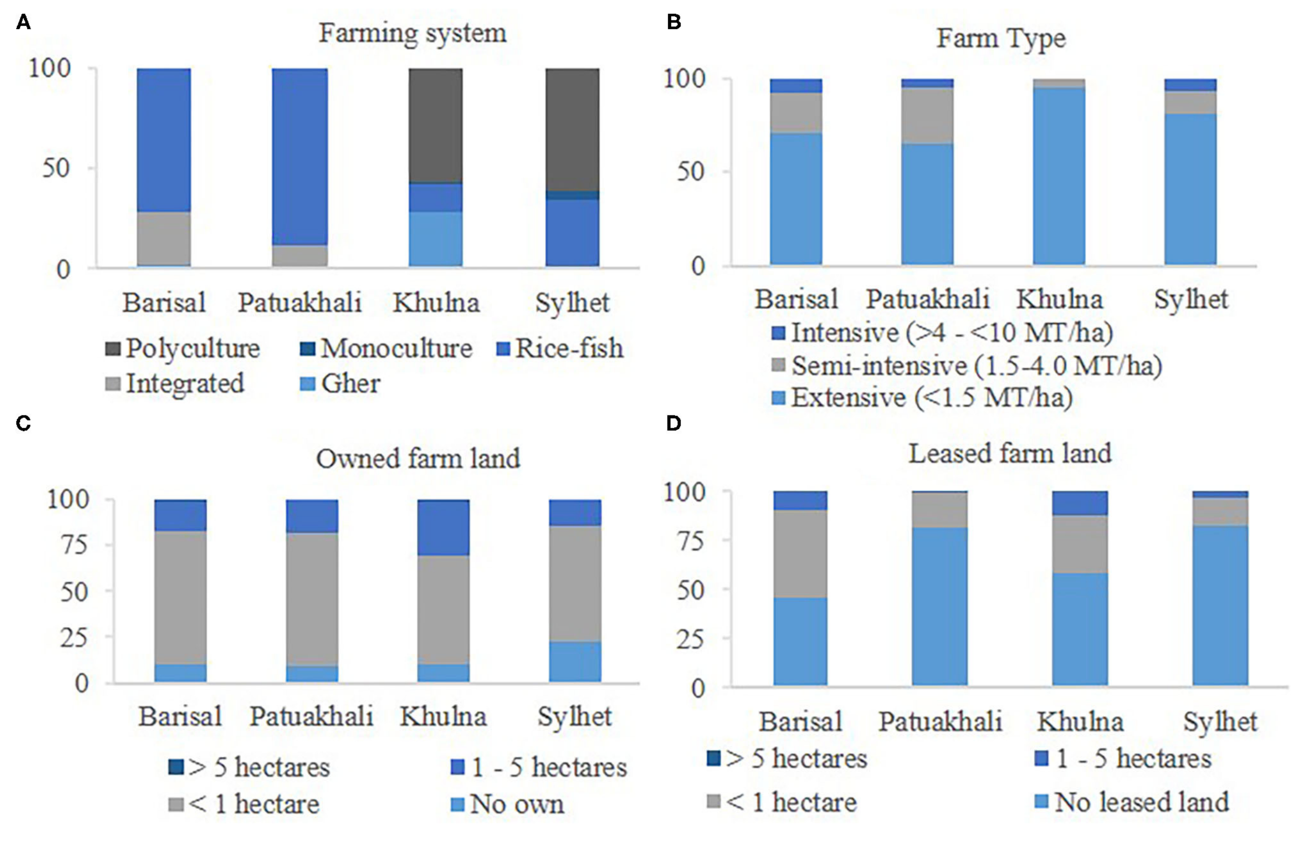

FIGURE 2 | Overview of fish-farming practice in the studied regions by percent of respondents.

(2 years). The family type is mostly joint, and family size tends to be small, except in Sylhet (**Table 1**). Aquaculture systems are dominated by rice fish in Barisal and Patuakhali and by fish polyculture in Sylhet and Khulna (**Figure 2A**), typically extensive farming types (<1.5 MT/ha production) across the studied districts (**Figure 2B**). Production takes place on both owned (**Figure 2C**) and leased farmland (**Figure 2D**) and on <1 ha. However, the use of leased farmland is relatively less common than owned. Fishpond area, pond depth, pond type, and ownership within these farming systems do not vary significantly across the districts (**Figure 3**). Between 67 and 100% of fish farmers have ponds larger than 0.03 ha (**Figure 3A**), mostly shallow (**Figure 3B**), perennial (**Figure 3C**), and owned (**Figure 3D**). Thirty to 65% of farmers surveyed had more than 10 years of experience in fish production (**Figure 4A**); however, 63–91% of farmers acknowledged that they had no formal training in aquaculture (**Figure 4B**).

Farmers' Fish-Crop Selection and Management Information in 2018

Carps (37–46%) and tilapia (38–45%) are the most widely cultured fish species across the study regions followed by freshwater prawn (1–33%) (**Figure 5A**). The greatest productivity, however, comes from pangasius (*Pangasius pangasius*) followed by carps and tilapia (**Figure 5B**). In addition, farmers have identified four key management interventions applied during the study year as well as 14 different climatic and non-climatic factors that influence their management decision-making process (**Table 2**). The calendar also shows that fish-farming operations usually (76–100%) start in April with pond preparation and end in December with harvesting. Fingerling collection, stocking, and grow-out management activities typically begin in April–May and continue up to September–October. Both climatic (such as the first monsoon/seasonal rain, heavy rain, floods, water quality and availability, high/low temperatures, and drought) and non-climatic factors (such as credit availability, tradition, disease outbreaks, fingerling prices and availability) influence the identified fish-farming operations. However, grow-out management operations, including feeding, fertilization, and pest and disease control, are mainly timed in relation to climatic factors (**Table 2**).

Knowledge of Fish Farmers on the Impacts of Climate Variability and Use of Climate Information for Aquaculture

Across the study districts, most of the fish farmers responded that they do not face considerable difficulties in fish production in relation to a particular climate variability (**Figure 6**). This

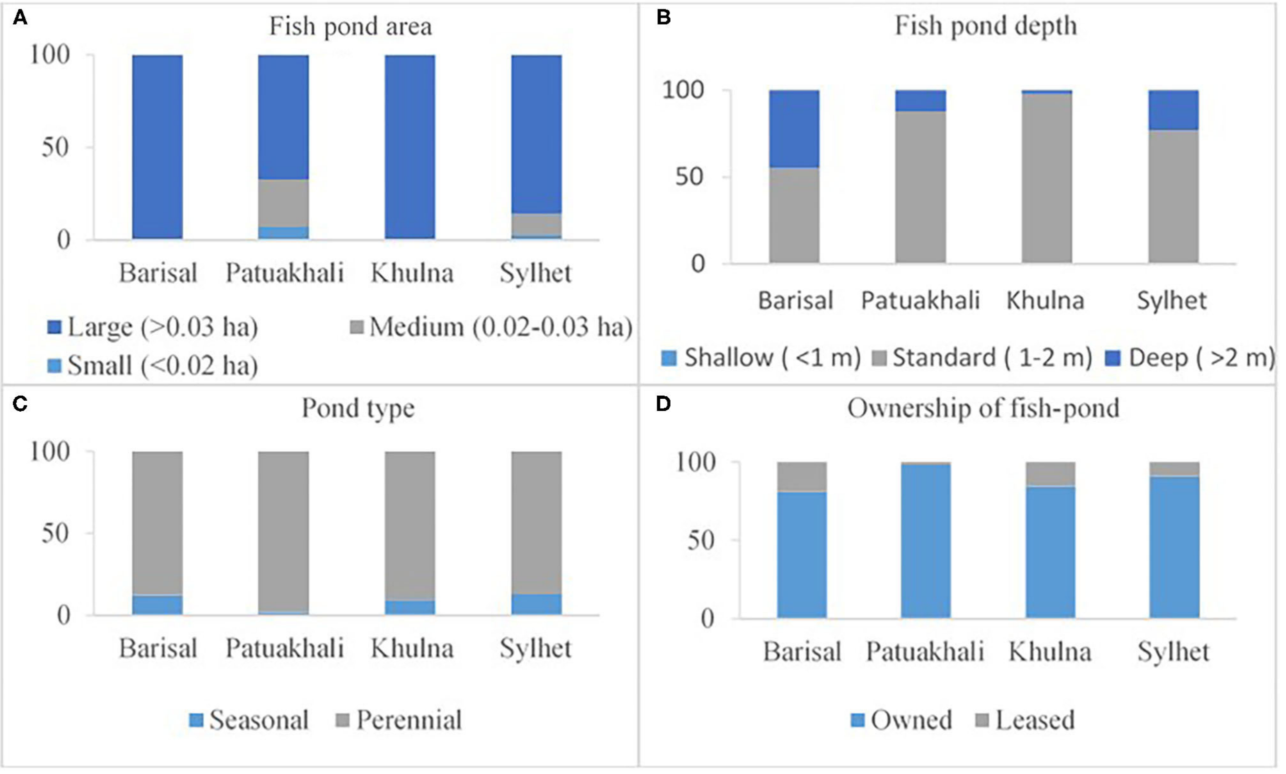

FIGURE 3 | Overview of fishpond information in the studied regions by percent of respondents.

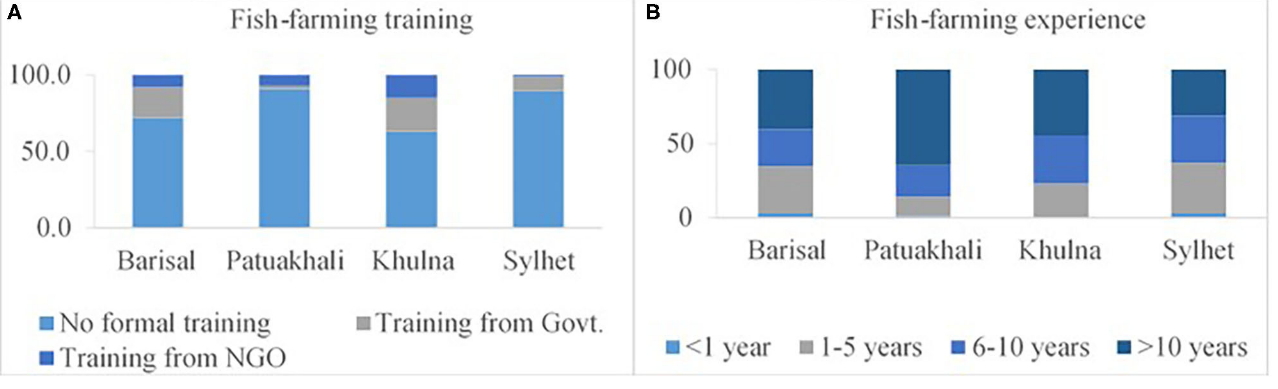

FIGURE 4 | Overview of fish-farmer type in the studied regions by percent of respondents.

result also indicates low awareness among farmers of indirect weather impacts on water quality and, hence, fish productivity. A similar result of farmers' low awareness of climate impacts on different coastal systems was reported by Hossain et al. (2018). However, those who responded positively identified high temperature, heavy rainfalls, and dry and cold spells as impacting climatic variables. Fish producers from Barisal (94%), Patuakhali (93%), and Khulna districts (50%) recognized high temperatures as the most challenging weather condition affecting their farms, while respondents from Sylhet suggested that heavy rainfalls and cold spells (both 33%, respectively) were most problematic. Respondents also identified five aquaculture management operations, namely pond preparation, fingerling collection and stocking, feeding, provision of inputs, and harvesting, which are sensitive to climate and weather variability (**Figure 6**). Conversely, information on the farmers' use of weather forecasts and climatic information suggested that 54–85% of the respondents do not currently use any climate information to assist in any aquaculture management operations (**Figure 7**). Those that use weather forecasts emphasized using

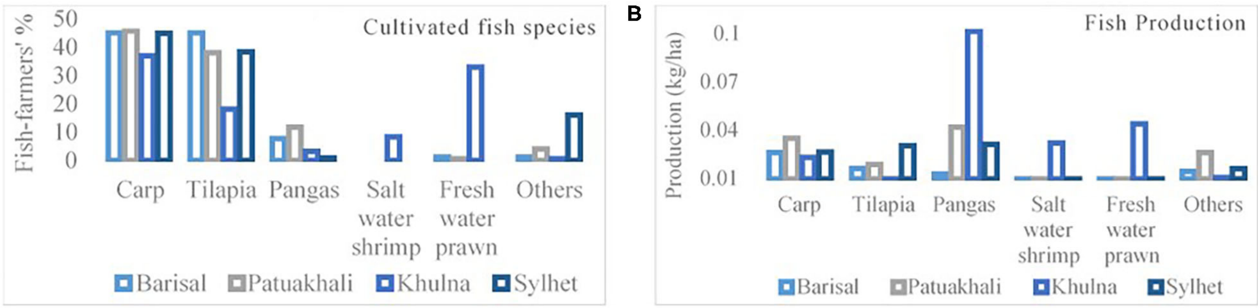

FIGURE 5 | Fish species cultivated and corresponding production levels in 2018.

them to prepare for heavy rainfalls (44–58%) and high temperatures (33–42%). The sources of this information are largely television and radio (**Figure 7**).

Responses of Fish Farmers on Climate-Sensitive Aquaculture Operations and Management Decisions

Feed management was recognized as the most sensitive part of aquaculture management conditioned by extreme weather events including heavy rainfalls (13–43%), dry spells (14–28%), high temperatures (30–44%), and cold spells (25–50%). Accordingly, farmers indicated that they respond to these conditions by halting fish feeding during heavy rain and by reducing feeding during high temperatures and both dry and cold spells (**Figure 8**). Respondents also distinguished fingerling collection and stocking as particularly sensitive to heavy rainfalls (38–47%), high temperatures (9–29%), and cold spells (13–27%). The primary action taken by farmers was to avoid collecting or stocking fingerlings during these conditions. Applying input materials (like fertilizer application, aqua-medicine use, managing irrigation, using aerator, etc.) is another sensitive part of aquaculture operations affected by all the identified climate variabilities. Respondents, therefore, prescribed decisions to stop using fertilizer and aqua-medicine during heavy rains, reduce fertilizer application, and manage irrigation during dry spells. Farmers also suggested that using a water aerator and adding water to adjust pond water level are common actions for responding to high temperatures. Conversely, no management conditions were identified for cold spells. Moreover, while pond preparation and harvesting were also identified as operations that are sensitive to temperature and rainfall variabilities, no management modifications were cited by farmers as common practices.

Lead Times and Preferred Platforms for CIS

Across the study districts, most of the fish producers (41–49%) preferred having at least a 7-day lead time to use forecasts from a CIS, followed by 15 days (23–31%) and 5 days (14–22%). A few were interested in having a monthly (1–5%) or seasonal (6–8%) service (**Figure 9A**). Regarding the CIS platform, almost all the respondents (80–97%) preferred direct voice call as their first preference; however, the second preference was for TV (with up to 43% farmers) (**Figure 9B**).

Key Informants' Responses on Climate-Sensitive Aquaculture Operations and Management Decisions

Similar to farmers, key informants identified high temperatures, cold and dry spells, and heavy rains as key weather phenomena that could affect different aquaculture operations, particularly water quality management, feeding, fingerling stocking, and harvesting (**Table 3**). According to key informants, high temperature plays a substantial role in water quality management, decreasing water pH (acidic/basic water), causing an imbalance in dissolved O_2 (oxygen) and CO_2 (carbon dioxide), and accelerating the generation of NH_3 (ammonia) and H_2S (hydrogen Sulfide) gas. These changes in pond water quality parameters can result in fish physiological stress, including reduced digestion capacity and food intake, both of which can reduce survival rate. To manage these challenges, the application of agricultural lime tends to be recommended. In addition, disinfectants, using a *horra* (a locally made tool for raking the pond bottom), zeolite, adding water, and supplying artificial O_2 through aeration can help in maintaining water quality. Reduced feeding or stopping feeding in the afternoon and providing a vitamin C supplement in the morning are also prescribed for good fish growth during periods of high temperatures. In addition, respondents suggested that stocking fingerlings during high temperatures in the afternoon should be avoided to reduce shock. Conversely, they suggested that cold spells can increase the pH and cause imbalances in dissolved O_2 and CO_2, which can result in longer residence times at shallow depths and reduced food intake. In this situation, key informants suggested restricting the use of lime, implementing irrigation, providing O_2 using either an aerator or oxygen-promoting aqua-medicines, reducing feeding, and if needed encouraging partial harvesting to reduce the density of the fish stock. During heavy rainfalls, the levels of dissolved O_2 and pH can decline. Combined with a sudden drop in temperature, this can result in reduced food intake and potential mortality. To reduce these risks, aeration is beneficial for increasing the supply of

TABLE 2 | Fish-crop calendar in study districts considering factors identified by farmers as contributing to operational and management decisions in the 2018 production season.

Months / Operations	Fish-crop calendar												Months / Factors
	January	February	March	April	May	June	July	August	September	October	November	Dececmber	
Pond preparation (PP)													First monsoon rain Water availability Seasonal rainfall Credit availability
Fingerling collection and stocking													Fingerling price Seed availability Credit availability Water availability
Grow-out management (GM) like													Water quality Disease outbreak Heavy rain Drought
Partial/full harvest (HH)													Flood Traditional Price Heavy rain

Respondents %	Operations			
	PP	FS	GM	HH
0–25				
26–50				
51–75				
76–100				

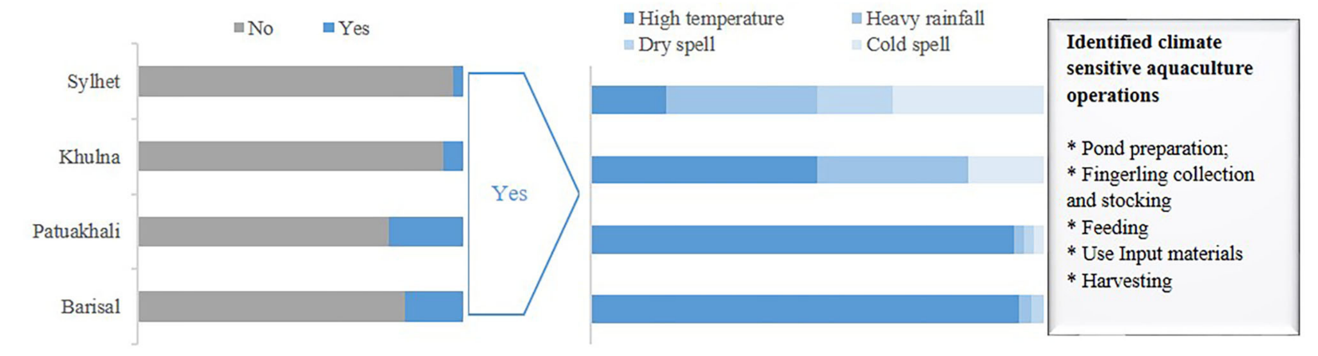

FIGURE 6 | Fish-farmers' responses on difficulties encountered in aquaculture resulting from perceived climatic variability.

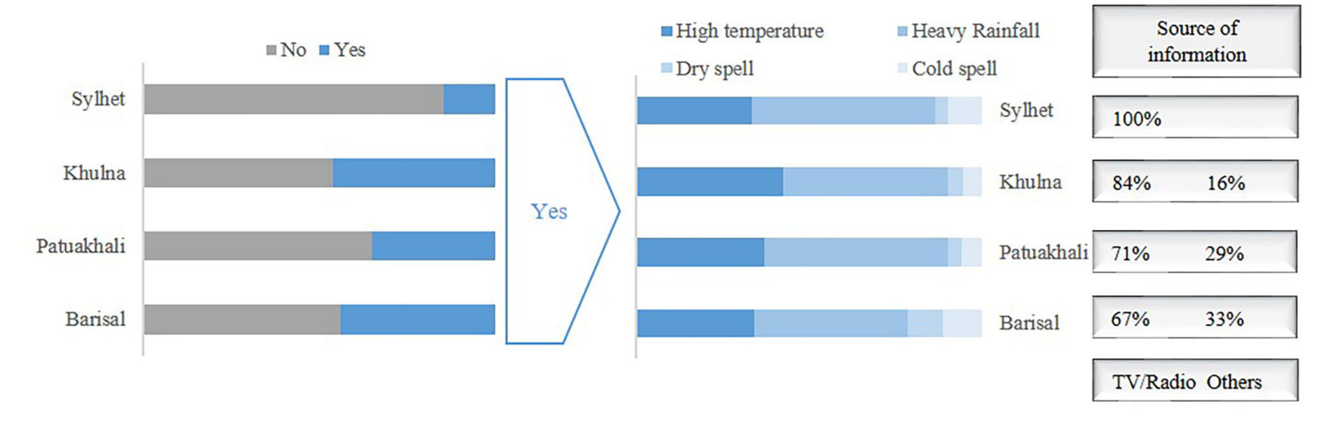

FIGURE 7 | Current extent of weather forecasts used by fish producers in study districts.

dissolved O_2 as well as applying lime after a heavy rainfall. An extremely heavy rain can result in pond flooding and also fish stocks escaping from enclosures. Key informants therefore suggested that farmers heighten pond banks and use nets to protect against losses. Conversely, dry spells were cited as conditions that reduce water availability because of evaporation from high temperatures, which can also affect feeding behavior and, under some circumstances, create ideal conditions for a disease outbreak. Respondents suggested that to manage these challenges, farmers can add water to ponds from ground water using pumps, or they can delay or reduce fingerling stocking. Farmers can also consider partially harvesting their ponds to reducing stock density while also adjusting feed supply.

Water Temperature and Rainfall Thresholds During the Grow-Out Phase for the Most Widely Cultured and Economically Important Fish Species in Bangladesh

Nile tilapia, rohu, freshwater prawn, and black tiger shrimp are the most widely cultured and economically important fish species for aquaculture in the study districts, as well as in Bangladesh as a whole (**Table 4**). Lower temperature (pond water) thresholds for tilapia and rohu were identified by key informants as between 20 and 22°C with standard deviation (SD) of 0.4 and 0.6, while the upper temperature threshold was between 32 and 30°C with SD of 0.5 and 0.7, respectively. For freshwater prawn and black tiger shrimp, similar upper and lower thresholds were identified as between 25 and 30°C with SD of 0.5 and 0.6. Conversely, upper temperature thresholds for tilapia and rohu were both identified as 31°C from the literature with SD of 2.9 and 2.4, while the lower limit was between 23 and 22°C with SD of 4.7 and 3.8, respectively. For freshwater prawn and black tiger shrimp, similar upper and lower thresholds were identified as between 26 and 33°C from the literature with SD of 4.1 and 1.8, correspondingly. Rainfall thresholds and the length of rainfall cessation provided by the meteorological experts from BMD were similar for all the species to identify dry spells as well as heavy and very heavy rainfalls (**Table 4**). When rain is <3 mm for 5 consecutive days during the monsoon season (June–September) and <1 mm for 5 consecutive days during the pre-monsoon (March–May) and post-monsoon (October–November) seasons, experts suggest that fish production could be negatively affected. Lastly, rainfall >44 mm/day was identified as heavy, while >88 mm/day was identified as the threshold for very heavy rain.

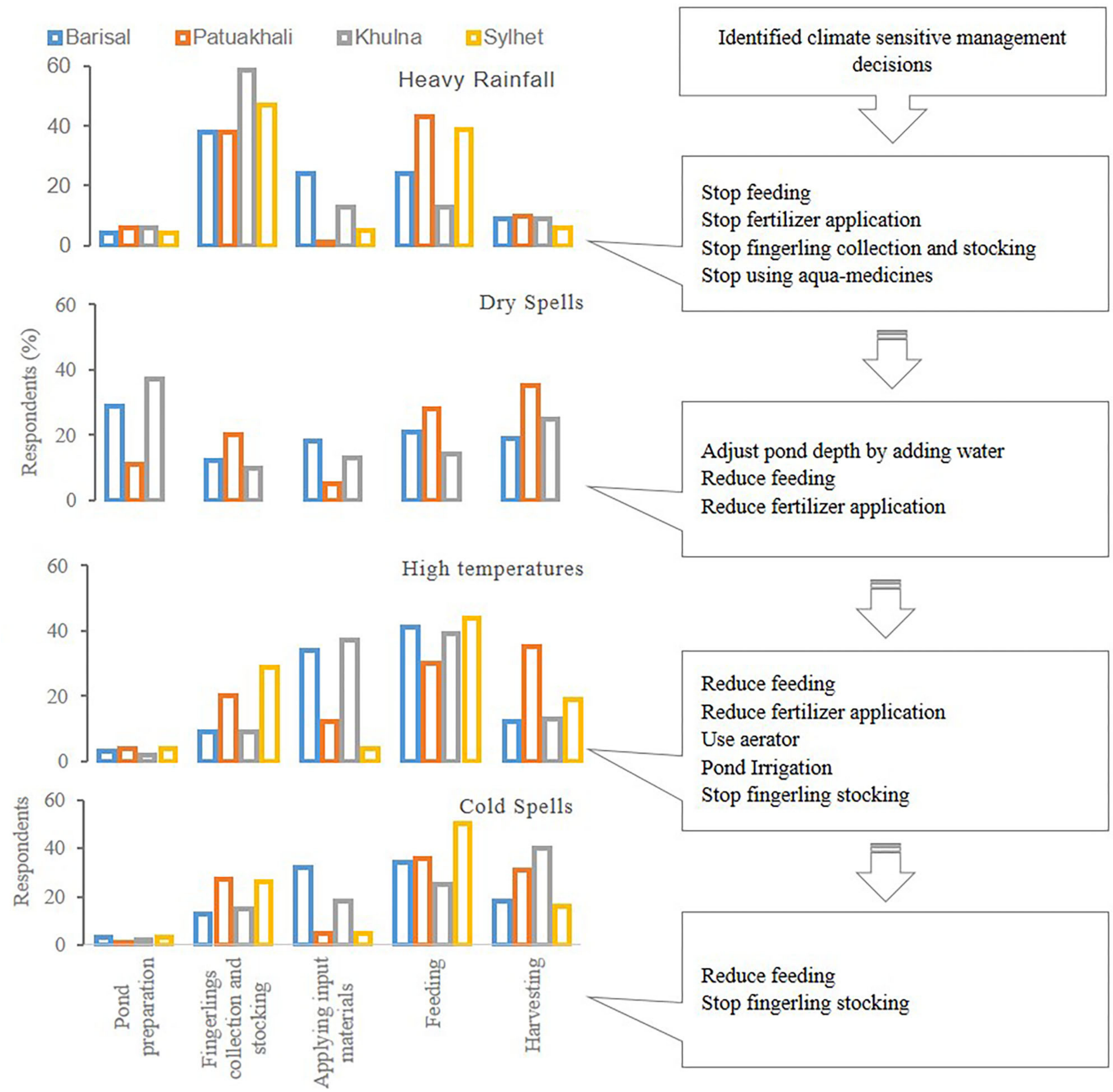

FIGURE 8 | Climate sensitive aquaculture operations identified by farmers in relation to specific types of weather events and consequent management decisions.

Framework for Making Climate-Responsive Decisions Based on Temperature and Rainfall Thresholds

Based on the temperature and rainfall thresholds (with the lowest SD), we developed two different decision frameworks for the four most widely cultivated and economically important fish species in Bangladesh along with appropriate stock management responses (**Figures 10**, **11**). As the intended CIS is to support smallholder fish farmers in managing their ponds and in aquaculture operations, a timeline is selected for the appropriate months of the grow-out phase of each species for both decision frameworks. For tilapia and rohu, the grow-out phase starts in May and ends in November, while for bagda (saltwater shrimp), it is from March to June, and for golda (freshwater prawn), from July to November. The conditions for the temperature decision framework are the maximum (Tmax) and minimum temperature (Tmin) thresholds of each species identified in **Table 4**. When the temperature goes above or below the critical limits of a particular species, the decision framework is triggered to the relevant decision points (such as water quality, feeding, and

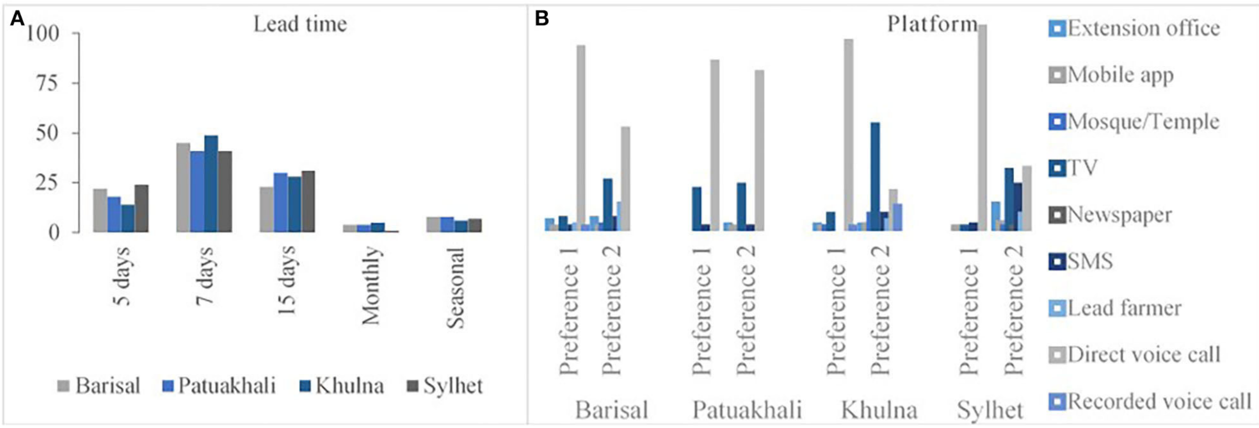

FIGURE 9 | Preferred lead times to make decisions to change management practices and preferred platforms for climate information services delivery.

TABLE 3 | Potential impacts of climate variability on aquaculture operations, potential management responses, and their intended effects, as described by the key informants.

Climatic variability	Climate-sensitive aquaculture operations	Potential impacts	Climate-sensitive management decisions	Expected outcomes
High temperature	Pond water quality management	Increased bacterial decomposition and decreased pH level	Lime application	Improved pond water quality Reduced risk of fish disease outbreak Reduced stress on fish physiology Optimal growth of fish stock Reduced mortality rate Enhanced production Reduced climate-induced losses Reduced climate-induced risks Good profit Availability of healthy and nutritious fish Ensured nutrition security Ensured food security Ensured sustainability of aquaculture Ensured livelihood security
		Low dissolved oxygen Imbalance between dissolved O_2 and CO_2 levels	Pond irrigation Aerator or any oxygen promoter aqua-medicine use	
		Increase in NH_3 and H_2S gas	Horra pulling and zeolite application	
	Feeding	Reduced digestion capacity Less food intake	Reduced feeding Apply nutritious food having vitamin C supplement during morning time	
	Fingerling stocking	Low survival rate	Avoid fingerling stocking during noon time	
Cold spells	Pond water quality management	Increased pH level	Restrict lime application	
		Imbalance between dissolved O_2 and CO_2 level	Pond irrigation to increase water depth Aeration to enhance dissolved oxygen in water Oxygen enhancing aqua-medicine	
	Feeding	Less food intake	Reduce feeding	
	Harvesting	Abnormal behavior of fish (e.g., floating near the water surface)	Reduce fish stock density through partial harvesting	
Heavy rain	Pond water quality management	Decreased dissolve O_2 level Decreased pH level Sudden temperature drop	Artificial oxygen supply using aerator or oxygen enhancing aqua-medicine Lime application after the rain	
	Feeding	No food intake	Stop feeding	
	Fingerling stocking	High mortality rate	Stop fingerling stocking	
	Harvesting	Flooding Fish escape	Heighten the pond banks Protect the fish to escape using nets	
Dry spells	Fingerling stocking	Lack of availability of surface water Delayed stocking Less production	Manage ground water supply using pumps Limit fingerling stocking	
	Pond water quality management	Sudden temperature rise Disease outbreak	Manage ground water supply using pumps Increase pond depth Reduce fish stock density Partial harvesting	
	Feeding	Less food intake	Reduce feeding	

TABLE 4 | Temperature and rainfall thresholds for the four mostly cultured and economically important fish species during the grow-out phase in Bangladesh.

Fish species	Temperature thresholds in °C								Rainfall thresholds (mm/day)		
	Lower limit				Upper limit				Dry spell	Heavy	Very heavy
	Expert opinion		Literature review***		Expert Opinion		Literature review		Identified and approved by the Bangladesh Meteorological Department		
	Average	Standard deviation	Average	Standard deviation	Average	Standard deviation	Average	Standard deviation			
Nile tilapia (*Oreochromis niloticus*)	20	0.4	23	4.7	32	0.5	31	2.9	<3* <1**	>44	>88
Rohu (*Labeo rohita*)	22	0.6	22	3.8	30	0.7	31	2.4	<3* <1**	>44	>88
Black tiger shrimp (*Penaeus monodon*) and Freshwater prawn (*Macrobrachrium rosenbergii*)	25	0.5	26	4.1	30	0.6	33	1.8	<3* <1**	>44	>88

**Rain for five consecutive days during monsoon.*
***Rain for five consecutive days during pre-monsoon and post-monsoon.*
****Reviewed literature is listed in the **Supplementary Material 2**.*

harvesting). It suggests modifications in management practices that can be presented to farmers as part of a CIS (**Figure 10**). On the other hand, the conditions for the rainfall decision framework include thresholds for very heavy rain, heavy rain, and dry spell. Thresholds do not differ by species during their grow-out phase and are, hence, applicable across the studied species. When rainfall forecasts exceed a threshold, the decision framework triggers the advice of appropriate management decisions for protective measures, feeding, harvesting, and water quality and availability (**Figure 11**).

DISCUSSION AND CONCLUSIONS

As highlighted in the *Introduction*, no CIS system is currently available for aquaculture in South Asian countries that provides actionable species-specific advisories for aquatic farmers based on weather forecasts and thresholds. The reason, rooted in a global lack of extensive research or pilots on climate services for aquaculture, is the absence of a fish species-specific climatic threshold and climate-sensitive management information that can lead to effective advisories and, thus, reduce climate variability-induced risks. The current work has not only identified climatic thresholds and management decision points based on expert opinions and a literature review to create a decision framework, but it has also captured fish-farmers' perceptions on CIS for aquatic food systems. Considering social perceptions is key to success for building the resilience of a particular system (Hossain et al., 2018). The absence of formal aquaculture training for most of the farmers (**Figure 3B**) and a lack of knowledge on climate variability impacts on aquatic food systems (**Figure 6**) also indicate the need for capacity development of fish famers alongside raising awareness about weather impacts on aquatic food systems and, thus, productivity (Kumar et al., 2020b). The potential of such awareness-raising activities is highlighted by the higher number of informed respondents in Barisal and Patuakhali, which are hotspots of CIS research and development projects, such as agriculture climate services for mungbean (e.g., CSISA—https://csisa.org/csisa-bangladesh/). The higher frequency of climatic extreme events in the south-west coastal region is also responsible for this heightened awareness.

Besides, the low percentage of women respondents' participation (2–8%) during the fish-farmers' survey (**Table 1**) recognizes the need of empowering women in small-scale aquaculture decision-making in a substantive way. The low participation of rural women respondents may be due to their perception of fish farming as a full-time occupation of men (Halim and Ahmed, 2006), social restrictions, and the inability to access property, especially land that limits participation in economic activities like aquaculture (Kruijssen et al., 2018). Women's engagement to secondary or supplementary fish-farming activities, such as preparing feed, making and maintaining fishing nets, repairing and maintaining other fishing equipment, sorting of fingerlings, and post-harvest processing resulted only in restricted decision-making roles so far (Quddus et al., 2018).

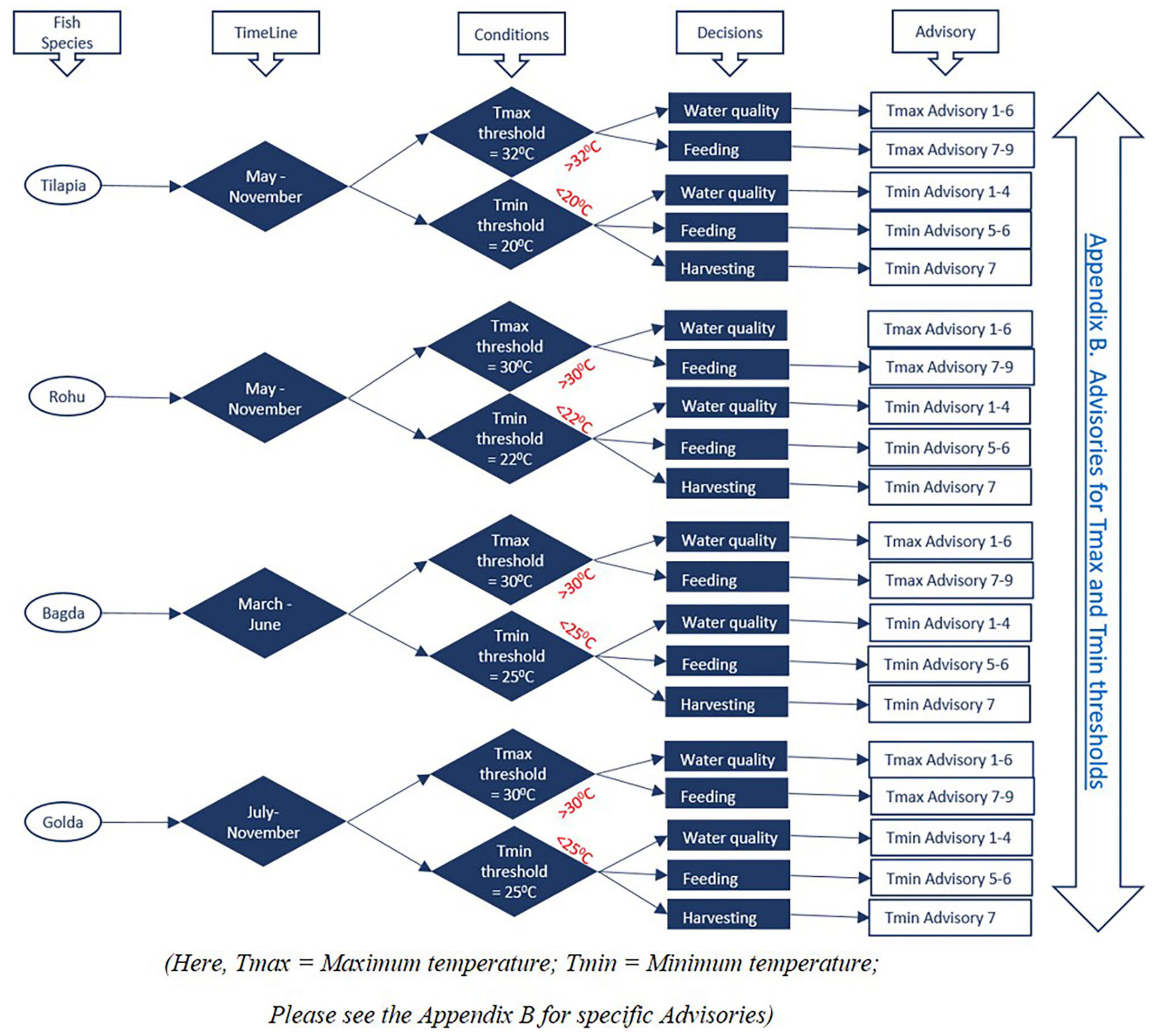

FIGURE 10 | Decision framework based on temperature thresholds for four widely cultivated aquatic species in Bangladesh.

Decision frameworks and threshold developments are conducted already for crop agriculture in Bangladesh (Krupnik et al., 2018), but the effort has not, so far, been recorded for aquaculture. Although only two fish and two crustacean species are currently included in the decision framework, the work is intended to spur additional research to include more species of economic importance. The choice of lead time and the systematic formulation of messages can make sure that available climate information is used to develop usable advisories (Singh et al., 2018). Most of the decisions are practical with a lead time of 3–5 days. A literature search of major aquaculture and climate service journals, as well as an internet search, found limited information upon which to develop species-specific decision frameworks for aquaculture, so a discussion with comparable studies is difficult. The decision framework presented here is modeled on the decision frameworks developed for crops under the Agvisely platform initiated by CIMMYT (https://www.agvisely.com); however, it is widely endorsed and developed for partner agencies of the Government of Bangladesh, such as the Bangladesh Agriculture Research Council and the Department of Agriculture Extension. The decision framework is expected to be integrated into the platform to offer the CIS for aquaculture, especially targeting extension agents connected to farmers. Farmers showed preference for voice calls (or recorded voice calls) for the climate service, but it can be prohibitively expensive to deploy voice calls to millions of farmers, unless there is

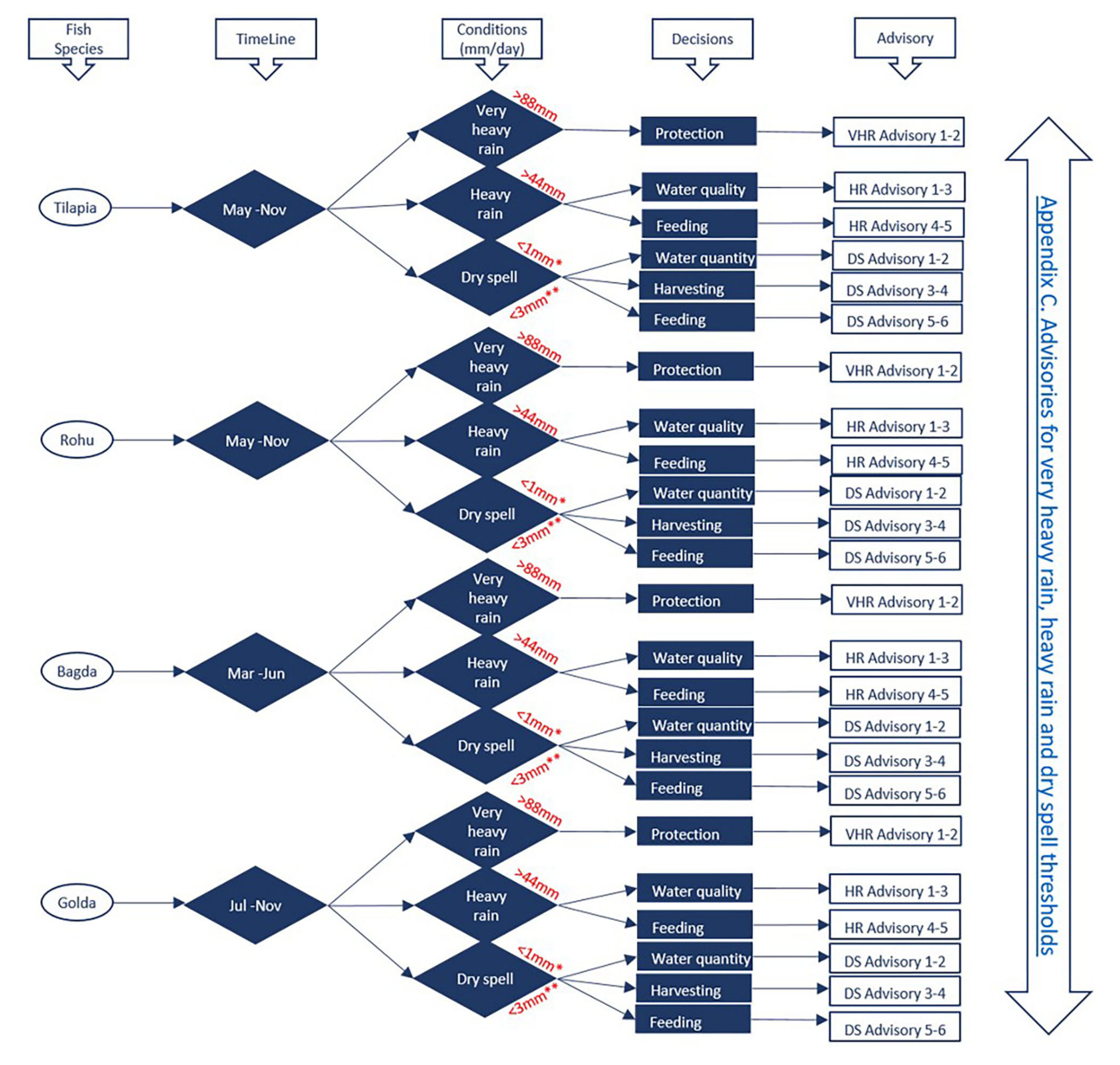

FIGURE 11 | Decision framework based on rainfall thresholds for four widely cultivated aquatic species.

willingness to pay for such services. This situation suggests a need for additional exploration on business models for climate services.

When integrated into the Agvisely climate service system, the decision framework will be able to trigger advisories for aquaculture farmers e.g. for pond water quality maintenance and feed management advice for tilapia once a weather forecast indicates that water temperatures are expected to breach 32°C in the next 5 days. Accordingly, fish farmers who have tilapia in their ponds at the grow-out phase can apply lime and use aerators to balance the pH and dissolved oxygen level. They can pump in additional water, perhaps using shallow or deep groundwater tube wells (**Appendix B**). It is to be noted that area-specific air and water temperature relationship will be integrated to operationalize this service. Similar Tmax advisories are applicable for the other three species, however, Tmax thresholds themselves differ (**Figure 10**). Conversely, temperatures below 20°C trigger Tmin advisories for water quality management, feeding, and harvesting modifications for tilapia. As a result, fish farmers can use advisory information to make decisions to turn on aerators, adjust pond water level, and apply lime to control pH. Generally, these advisories will be applicable for other species as well, depending on their Tmin thresholds. Similarly, if a rainfall exceeds 88 mm/day during the grow-out phase of the selected fish species, farmers are advised to consider protection measures for fish enclosures. Fish farmers can heighten pond banks and also use nets to prevent the fish from escaping (**Appendix C**). For heavy rain (>44 mm/day), the decision framework suggests options for pond water quality and feed management, including using aerators to increase dissolved O_2 or applying lime to reduce water acidity. Farmers may also consider stopping feeding. Moreover, for dry spells (<1 mm/day during the pre-monsoon and post-monsoon seasons and <3 mm during the monsoon season for 5 consecutive days), fish farmers are advised to consider increasing the water supply to their ponds or to do a partial harvest along with reduced feeding.

Currently, the decision framework considers rainfall and temperature thresholds for tilapia and rohu, saltwater shrimp, and freshwater prawn species that trigger climate-sensitive management decisions along with specific advisories at different operations, such as fingerling collection and stocking, feeding, using input materials, and harvesting. The temperature thresholds trigger actions like aeration, irrigation, applying lime or zeolite, feeding, or harvesting decisions. Similarly, rainfall thresholds trigger advice on protection of fish and pond water quality and feed management, as well as pond watering decisions. Pond preparation was also identified as a major climate-sensitive decision, which is mainly affected by the onset of monsoon and not currently included in the decision framework as it is currently focused on the grow-out phase of the selected species. The next step for developing the climate advisory is to embed nationally endorsed weather forecasts from the Bangladesh Meteorological Department with the decision framework and deliver the advisories to farmers, likely through the Agvisely platform. Once integrated to the platform, an evaluation on the contribution of the CIS in preventing large-scale economic damages as well as enhancing productivity and overall resilience capacity of fish farmers will be carried out. It is expected that the service can create large economic benefits to farmers who are highly vulnerable to temperature and rainfall variability (Rao et al., 2019).

In addition to practical implications, the present study contributes to the emerging literature of climate services for aquatic food systems. For instance, this study identifies the sensitivity of different aquaculture operations to variability of temperature and rainfall. The work also extends the current understanding on using CIS for reducing short-term climate risks in aquaculture operations by recognizing five climate-sensitive management decision points and 26 potential advisories in line with variability of temperature or rainfall. Moreover, the comprehensive analysis based on three sources of information (fish-farmers' response, expert interviews, and literature review) of this study presents a method for developing decision trees based on specific climatic condition in relation to a particular fish species for the grow-out phase. This innovative decision support approach is to our knowledge the very first endeavor to develop species-specific temperature and rainfall thresholds based on CIS for South Asian aquaculture system to reduce climate risks.

The limitation of the decision framework currently is that it has included a limited number of species and identified only grow-out phase climatic thresholds and related advisory for the selected species. It could benefit from a horizontal expansion to a number of other finfish and shellfish species to cater to the needs of farmers cultivating these species and also vertical extension to other stages of growth like breeding and spawning to assist other value chain actors (i.e., hatchery managers). Secondly, the farmers demanded a lead time of 7–14 days; however, the advisories currently prescribed are limited to those that can be implemented within 5 days of lead time, which is highly reliable (appreciable skill in forecasting) in Bangladesh context (Kumar et al., 2020a). As the forecast skill in Bangladesh improves in the future (World Bank, 2018), additional actions with extended lead time can be included. However, fish-farmers' preference for 7–14 days of lead time is to secure resources for executing the management advisory, such as equipment, fertilizers or aqua-medicines, and labor. They need time to hire pumps (if not owned) for irrigating the ponds during a dry spell, arranging an aerator for maintaining water quality during high temperatures, and organizing labor and necessary implements for raising pond dikes or netting the pond during heavy rain. Also fish-farmers' preference for direct voice call may have a connection with low smartphone penetration in the rural areas than in the urban area of the country as well as with additional expenditure for continuous internet connection in using apps or other digital platforms (MoPTI, 2020). The current work reports a valuable first step in delivering aquaculture CIS to smallholder farmers that can provide clear actionable information in response to forecasted local climate conditions to manage climate risks and, thus, to reach the broader goals of ensuring livelihood, food, and nutrition security. The work mapped climate-sensitive decisions in aquaculture and developed advisories specific to growth stage and also timelines for four major species using multiple sources of information. If the efforts to develop a CIS using the specified decision framework become fruitful, it can offer significant positive benefits and act as a template for similar services in other countries. The expected outcomes are improved pond water quality, reduced disease outbreak, reduced stress on fish physiology, good growth of fish stock, reduced fish mortality rate, increased production, and reduced climate-induced loss, all of which ensure better profits for farmers and provide food and nutrition security to the population. It is expected that the decision framework will continue growing with more climate-sensitive decision points and additional fish species, and that it will become a mature climate service tool over time. Given the production of 2.4 million metric tons of fish in 2017–2018 from closed aquaculture systems in Bangladesh, an increase in production by 1% can provide 24,000 tons of fish that can cater to the yearly protein needs of one million people (at a recommended allowance of 60 g/day). This indicates the potential value creation and contribution to food and nutritional security by operationalizing an aquaculture climate service. The increased availability of fish also disproportionately benefits poorer communities, given their higher price elasticity of fish consumption. Given the challenges in sustaining capture fisheries, there is an increasing dependence on aquaculture for Bangladesh's fish supply. Therefore, ensuring climate smartness, especially higher production and resilience in aquaculture systems, is of critical value to overall food system resilience and sustainability. The provision of climate services can act as a risk reduction intervention, and the reduced risk levels act as a mechanism to increase investments in aquaculture by small farmers. The creation of the reported decision framework is a crucial step in realizing this promising opportunity.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/**Supplementary Material**, further inquiries can be directed to the corresponding author/s.

ETHICS STATEMENT

Ethical review and approval was not required for this study with human participants, in accordance with the local legislation and institutional requirements.

AUTHOR CONTRIBUTIONS

PH led the development of the paper, overall framing, data collection, analysis, and writing the manuscript. TA-B contributed in writing the discussion and conclusion section. TK, MB, EM, and MP critically reviewed the manuscript which went through multiple revisions by PR and TA-B. Finally, PR coordinated and integrated the co-authors input for finalizing the manuscript. All authors contributed to the article and approved the submitted version.

FUNDING

This research was supported by the CGIAR research program on Climate Change Agriculture and Food Security (CCAFS; https://ccafs.cgiar.org/)-funded project entitled Capacitating Farmers and Fishers to manage climate risks in South Asia (CaFFSA), by ACToday-the first of Columbia University's World Projects, and by the USAID and Bill and Melinda Gates Foundation (BMGF)-supported Cereal Systems Initiative for South Asia (CSISA). USAID, BMGF, and CCAFS do not necessarily endorse the findings of this paper, and the results of this paper shall not be used for advertising purposes.

SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fsufs.2021.677069/full#supplementary-material

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Conflict of Interest: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

frontiers in Sustainable Food Systems

ORIGINAL RESEARCH
published: 17 June 2021
doi: 10.3389/fsufs.2021.667297

Pathways of Climate Change Impact on Agroforestry, Food Consumption Pattern, and Dietary Diversity Among Indigenous Subsistence Farmers of Sauria Paharia Tribal Community of India: A Mixed Methods Study

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Edited by:
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Specialty section:
This article was submitted to Climate-Smart Food Systems, a section of the journal Frontiers in Sustainable Food Systems

Received: 12 February 2021
Accepted: 30 April 2021
Published: 17 June 2021

Citation:
Ghosh-Jerath S, Kapoor R, Ghosh U, Singh A, Downs S and Fanzo J (2021) Pathways of Climate Change Impact on Agroforestry, Food Consumption Pattern, and Dietary Diversity Among Indigenous Subsistence Farmers of Sauria Paharia Tribal Community of India: A Mixed Methods Study. Front. Sustain. Food Syst. 5:667297. doi: 10.3389/fsufs.2021.667297

Climate change poses severe threats to the social, cultural, and economic integrity of indigenous smallholder subsistence farmers, who are intricately linked with their natural ecosystems. Sauria Paharia, a vulnerable indigenous community of Jharkhand, India, are smallholder farmers facing food and nutrition insecurity and have limited resources to cope with climate change. Eighteen villages of Godda district of Jharkhand inhabited by Sauria Paharia community were randomly selected to conduct a mixed methods study. In 11 out of 18 study villages, we conducted focus group discussions (FGDs) to examine the perception of this indigenous community regarding climate change and its impact on agroforestry and dietary diversity. In all 18 villages, household and agricultural surveys were conducted to derive quantitative estimates of household food consumption patterns and agroforestry diversity, which were triangulated with the qualitative data collected through the FGDs. The FGD data revealed that the community attributed local climatic variability in the form of low and erratic rainfall with long dry spells, to reduced crop productivity, diversity and food availability from forests and waterbodies. Declining agroforestry-produce and diversity were reported to cause reduced household income and shifts from subsistence agricultural economy to migratory unskilled wage laboring leading to household food insecurity. These perceptions were supported by quantitative estimates of habitual food consumption patterns which revealed a predominance of cereals over other food items and low agroforestry diversity (Food Accessed Diversity Index of 0.21 $\pm$ 0.15). The adaptation strategies to cope with climate variability included use of climate-resilient indigenous crop varieties for farming, seed conservation and access to indigenous forest foods and weeds for consumption during adverse situations and lean periods. There were mixed views on cultivation of hybrid crops as an adaptation strategy which could impact the sustained utilization of indigenous food systems. Promoting sustainable adaptation strategies, with adequate knowledge and technology, have the potential to improve farm resilience, income, household food security and dietary diversity in this population.

Keywords: climate change, indigenous food systems, food consumption patterns, agroforestry, subsistence farmers, tribal community, smallholder farmers

INTRODUCTION

Climate variability and change influence ecosystems, food security, health, and other domains fundamental to human existence and well-being (Costello et al., 2009; International Labour Organization, 2017). Indigenous people, who are the earliest inhabitants of a geographical region, share historical, cultural and physical connections with the environment and manage about 28 percent of the earth's land surface (International Labour Organization, 2017). Rapid shifts in climate patterns have marginalized the livelihoods of already vulnerable indigenous populations globally, many of whom are predominantly smallholder subsistence farmers[1] relying on rain-fed agriculture. Their geographical location in environmentally fragile regions (such as hills, forests, deserts, and floodplains), expose them to temperature and rainfall variability and a variety of climate risks, (Morton, 2007; Walpole et al., 2013) threaten their delicately balanced subsistence cycle, increase the likelihood of poor crop yields, and reduce their accessibility to culturally valued resources (Morton, 2007; Arbuckle et al., 2013).

The indigenous tribal communities of India, recognized by the government as "Scheduled tribes" (STs), are characterized by traditional belief systems, financial insecurity, and poor health outcomes (Tribal Health in India: Executive Summary Recommendations, 2018). Jharkhand, a tribal-dominated state in the eastern part of India, is experiencing the impacts of climate variability and change (Wadood and Kumari, 2009; Government of Jharkhand, 2014; Kumar et al., 2016; Ahmad et al., 2018; Tirkey et al., 2018), characterized by frequent occurrences of long dry spells, monsoon variability and extreme heat. Analysis of climatic trends in the state reveals a sharp decline in annual rainfall levels in several districts, with increased frequency and severity of extreme weather events like heat wave during summers, pre-monsoon hail storms, and extreme frost/cold wave in winters (Government of Jharkhand, 2014). Almost all districts are affected by drought; many regions experience forest fires and lightning, with sudden occurrences of heavy rainfall (Minj, 2013; Ahmad et al., 2018). This climate variability and resultant changes impact impoverished tribal communities in Jharkhand, whose livelihoods are dependent on subsistence farming and forestry that are an integral part of their indigenous food systems (Misra et al., 2008; Bhattacharjee et al., 2009; Ghosh-Jerath et al., 2020a, 2021). Further, environmental destruction due to deforestation and land degradation results in diminished biodiversity and further affects the integrity and stability of the ecosystems adversely (Kayet et al., 2016). All these changes have a marked effect on the social, cultural, and economic integrity of the indigenous tribal communities who are intricately linked to these ecosystems (Kayet et al., 2016).

Particularly vulnerable tribal groups (PVTGs) of India, who are poor, marginalized communities characterized by a pre-agricultural system of existence, zero or negative population growth and extremely low levels of literacy compared to other tribal groups, could be the worst-affected communities from climate related outcomes (Minj, 2013). Sauria Paharia, one of the PVTGs residing on the far-flung hilltops of Jharkhand, have diminished social and financial capital; they practice small-scale shifting cultivation for their livelihood, which often results in abject poverty and poor health status (Maternal Health and Nutrition Report, 2014; Ghosh-Jerath et al., 2020a,b). Despite their biodiverse surroundings, they are malnourished and face extreme levels of nutritional deprivation (Ghosh-Jerath et al., 2020a,b). They have limited access to technical and financial resources and development assistance programs due to geographical inaccessibility, (Maternal Health and Nutrition Report, 2014; Jamwal, 2019) leading to increased vulnerability to climate shocks.

Although there is an increased interest at the level of policy-making to ensure food security among indigenous communities in the face of climate variability (Vermeulen et al., 2012; Climate-smart agriculture for food security, 2014), a lack of information regarding the experiences of the community and their coping strategies hinders adaptation efforts. This gap in knowledge is particularly significant for the marginalized groups like PVTGs, who perhaps lack entitlements to participate in any policy process. Few studies from Africa (Mapfumo et al., 2016; Ayanlade et al., 2017; Zamasiya et al., 2017; Aniah et al., 2019) and Central America (Roco et al., 2015; de Sousa et al., 2018) have explored the responses and resilience of the indigenous smallholder farmers to climate change. These studies have reported high levels of climate vulnerability among the indigenous farmer communities, with specific impacts on their food sources and ecosystem services. However, limited literature exists on perspectives of Indian smallholder farmers belonging to indigenous tribal communities (Minj, 2013; Sharma, 2019). Climate variability and change threatens farmers' food security and well-being in many tribal areas of Jharkhand (Minj, 2013; Sharma, 2019) and there is a need to have focused research on its impact on their food systems. This paper, hence, attempts to

[1]"Smallholder subsistence farmers" here refers to local food producers who own small, marginal lands (< 10 hectares), often employ family labor and mainly use the farm produce for household consumption. This category also includes people who depend on sale of livestock and livestock products, and are engaged in hunting and foraging foods from forests and water bodies for food and sustenance (Morton, 2007).

investigate perceptions about climatic variability, its influence on farming systems, food security, and local adaptation strategies among vulnerable Sauria Paharia tribes of Jharkhand, India. These findings are then discussed in the light of quantitative estimates of agroforestry diversity and household (HH) food consumption patterns in the community to triangulate multiple knowledge frames regarding climate variability impacts. The evidence base generated from this study will supplement the existing data on perceptions of indigenous smallholder farmers from different parts of the world, and may be helpful to understand their vulnerability and resiliency to climate variability in the Indian context.

MATERIALS AND METHODS

General Characteristics of the Study Area

The study was conducted in Godda district of Jharkhand, a part of Santhal Parganas division of Jharkhand. The region is formed of undulating uplands, long ridges and depressions and is replete with scattered hillocks covered with forests. The total district area is 2110.4 km^2, of which 35.2% is cultivable land and 11.2% is covered with forests (Godda District Administration, Jharkhand | India). The total scheduled tribe population is 279,208, which constitutes 21.26% of the total district's population (Census, 2011). Godda district has a tropical climate, with average summer temperatures hovering around 41 degrees Celsius, winter temperatures around 28 degrees Celsius and average annual rainfall of 1094.9 mm (Godda District Administration, Jharkhand | India).

Our study was focused in the geographically diverse Sunderpahari and Boarijor blocks of Godda district (**Figure 1**), with a high concentration of Sauria Paharia population (13,688) (Census, 2011). These two blocks were purposively selected to explore the impact of climatic variation in two geographically distant areas inhabited by the community. Sunderpahari has a total area of 433.4 km^2 and spreads across hilly terrain with nearly 50% of the land covered with forests. It has a total scheduled tribe population of 50,133, divided across 221 villages. Boarijor has a total area of 388.04 km^2 and is situated along both hilly regions and plains. The total scheduled tribe population of Boarijor is 76,935, spread across 309 villages.

Study Design and Sampling

This piece of research is part of a larger study which has used a mixed-methods approach for documenting the contribution of indigenous foods to nutrient intake and dietary diversity in tribal women and children of Jharkhand (Ghosh-Jerath et al., 2019). **Figure 2** represents the detailed methodological approach followed in the present study.

A two-stage cluster sampling design was followed to select the villages and the HHs from the purposively selected blocks of Sunderpahari and Boarijor. In the first stage of cluster sampling,

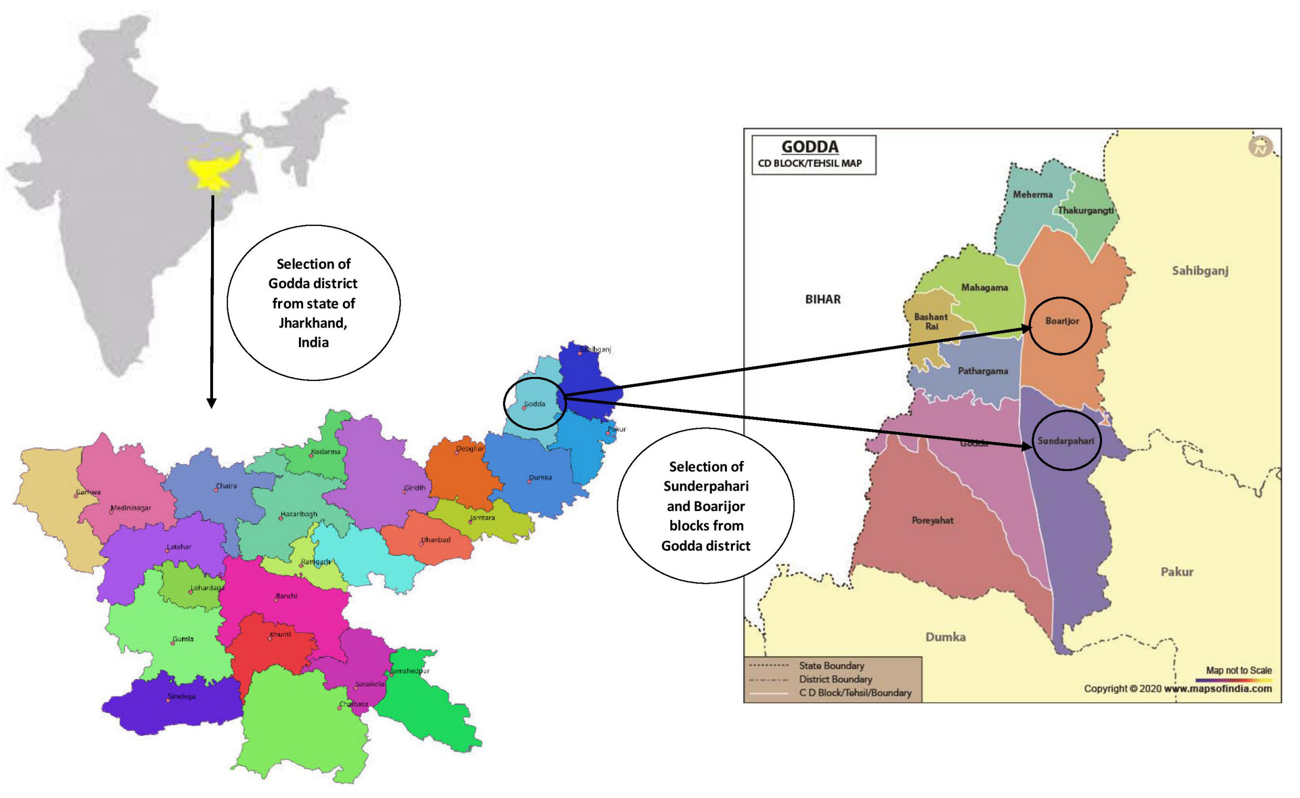

FIGURE 1 | Study landscape in Godda district of Jharkhand, India.

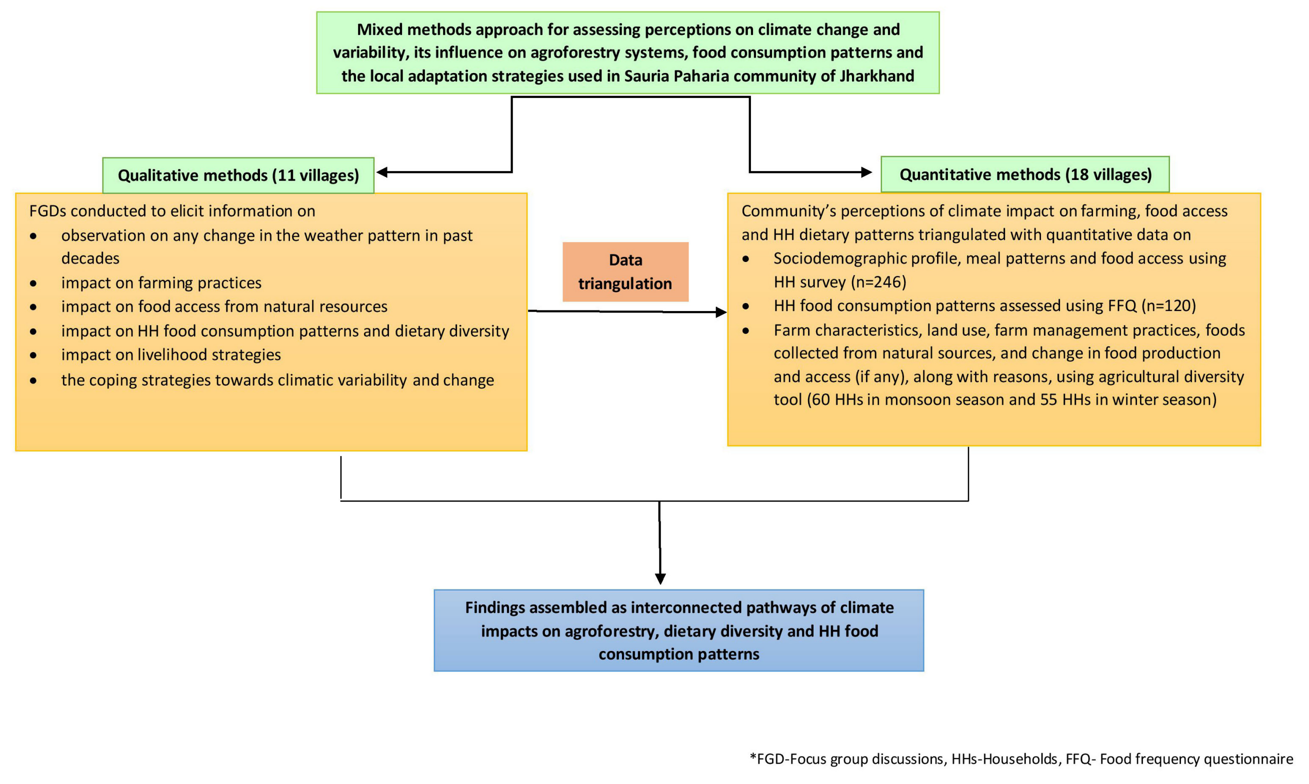

FIGURE 2 | Methodological approach used in the present study.

nine villages were randomly selected from each block (total 18 villages) using probability proportional to size sampling. Among these 18 villages, in March 2018, qualitative information was collected through focus group discussions (FGDs) from 11 villages (1 FGD per village) (6 villages of Sunderpahari and 5 villages of Boarijor) till the point of theoretical saturation. In the second stage of cluster sampling, all 18 selected villages were visited in June, 2018 and a house-listing exercise for all Sauria Paharia HHs was performed to construct the sampling frame of eligible HHs. The eligibility was based on the overall objective of the larger study and presence of at least 1 non-pregnant woman in the reproductive age group (15–49 years) and 1 child (6–54 months) in the HH. The eligible HHs were revisited in August 2018 for a detailed quantitative survey on HH level sociodemographic profile, food consumption patterns as well as HH access to different food sources.

Based on the overall objective of the study which explored the contribution of indigenous foods to dietary diversity and micronutrient intake, the requisite sample size (for quantitative survey) was calculated based on the difference in mean dietary intake of iron of 4 mg/day (35% increase) with a standard deviation (SD) of 7 mg/day between consumers and non-consumers of indigenous foods, reported in a previous study (Ghosh-Jerath et al., 2016) among women of Santhal tribes. Using the nMaster software (version 2.0) for sample size calculation, a sample size of 194 HHs was arrived at, with 80% power and a 5% level of significance, with a design effect of 2. Further details of the sample size calculation can be accessed elsewhere (Ghosh-Jerath et al., 2019).

Qualitative Data Collection

For the qualitative inquiries, the empirical data were gathered through FGDs conducted to elicit the community's perceptions of changes in the weather pattern and its impact on agriculture and coping strategies adopted. The respondents were selected using the snowball sampling technique (Naderifar et al., 2017) and represented different age groups to gather perceptions on past and present climatic conditions and their impacts (gender and age wise details are given in **Table 1**). The FGD guide was prepared by adapting questions from the tool "Climate Change and Food Security Vulnerability Assessment," developed by Bioversity International and the Institute of Development Studies (Ulrichs et al., 2016). The FGDs were conducted in Hindi and the native Paharia dialect, with the help of trained local field workers fluent in the native dialect. All the FGDs were recorded using a voice recorder. Respondents were asked to discuss their views on a variety of topics such as their observation on any change in the weather pattern in past decades, its impact on farming practices, access to foods from natural resources, food consumption status, livelihoods, and coping strategies toward climatic variability. The principal investigator moderated the discussions with the help of

TABLE 1 | Characteristics of FGD respondents in villages of Sunderpahari and Boarijor blocks of Godda district, Jharkhand, India.

Block	Study village	Respondent group size	Men	Women	Elderly	Young and middle-aged adults
Block 1	Village 1 Tasaria	9	5	4	✓	✓
Sunderpahari	Village 2 Kusumghati	7	1	6		✓
	Village 3 Paharpur	10	1	9	✓	✓
	Village 4 Chewo	8	4	4	✓	✓
	Village 5 Longodih	9	3	6		✓
	Village 6 Nadgoda	4	1	3		✓
Block 2	Village 1 Rajabhita	11	4	7	✓	✓
Boarijor	Village 2 Kusumghati	15	11	4	✓	✓
	Village 3 Lutibahiar	10	2	8		✓
	Village 4 Bara-amra	8	4	4		✓
	Village 5 Kortica	9	4	5	✓	✓

a research assistant (for notes taking and recording) and a local field worker.

Quantitative Data Collection

We conducted 246 HH surveys using a pretested structured questionnaire to elicit information on HH level sociodemographic profile, meal patterns and their access to different food sources. In addition to this, a detailed agricultural survey [adapted from Agricultural Questionnaire of the Third Integrated HH Survey, 2010-11, Malawi Government (National Statistical Office, 2011)] was administered on a conveniently selected sub-sample of 60 HHs in August 2018 (for a reference period of February to June 2018) and another 55 HHs in late January 2019 (for a reference period of July 2018 to January 2019) to capture detailed information on agricultural production and food access during the two cropping seasons (with sowing period during the monsoon and winter season, respectively). Using this tool, field investigators collected detailed data from the smallholder farmers of selected Sauria Paharia HHs on farm characteristics, land use, farm management practices, types of foods collected from different sources, and change in food production and access (if any), along with the reasons. The intent was to capture information on climatic variability (if any) as one of the possible reasons.

This information on HH food access and production (from HH survey and agricultural survey) was further utilized to construct an index called Food Accessed Diversity Index (FADI), which has been adapted from the crop diversity index (CDI) (Michler and Josephson, 2017). The FADI was created in order to provide an objective estimate of agroforestry diversity. For calculating FADI, the total number of foods grown, gathered or accessed and animals raised in a particular HH (n) were divided by the corresponding maximum possible number of foods grown, gathered, accessed and raised in a particular village (N). Foods accessed from the market were not included in this index. The FADI was expressed as

$$\text{FADI}=\left(\frac{\text{n}}{\text{N}}\right)^2$$

Lower values of FADI indicate lower diversity in production and access to foods and vice versa.

The frequency of consumption of different food items under various food groups at HH level was assessed using a food frequency questionnaire (FFQ). Food items were identified during FGDs conducted in the month of March and were extensively used to develop the FFQ that included both commonly consumed Indian food items as well as indigenous tribal foods from the region. We developed a 300-item FFQ and administered it on a conveniently selected sub-sample of 120 HHs during the monsoon season (August 2018). The questionnaire inquired about the frequency of consumption over the past 1 month without specification of portion size. Nine predefined frequency categories ranging from "never" to "2 or more times per day" were used.

All the questionnaires were piloted in the field prior to data collection. HH and agricultural surveys were administered using handheld tablets and CS pro software (Version 7.1), by a team of enumerators who underwent formal training. Paper forms were used for FFQ and administered by nutritionists and nutrition interns after due training. All surveys were conducted with either the HH head or family member in charge of the HH.

Data Analysis

FGDs were recorded and transcribed verbatim from Paharia to Hindi followed by translation of Hindi transcripts to English. The data were coded using Atlas.ti version 8. The data were first open coded and subsequently combined into key themes using a thematic framework analysis, for identifying, analyzing and generating relevant themes within the data (Braun and Clarke, 2006). For quantitative data, descriptive statistics were used wherein continuous variables were reported as mean ± standard deviation (SD) and categorical ones were summarized using

TABLE 2 | Household characteristics, food production and access of Sauria Paharia community in Jharkhand, India ($n = 246$).

Household characteristics	n (%)
House type	
Kaccha (mud/thatched roofs and walls)	190 (77.2)
Semi-Pakka (semi-cemented roofs and walls)	51 (20.7)
Pakka (cemented roofs and walls)	5 (2.1)
Source of cooking fuel	
Firewood/chips/grass/stems/straw/shrub	230 (93.5)
Kerosene	10 (4.3)
Others	6 (2.2)
Source of drinking water	
Tube well/Hand pump	177 (71.9)
Well	57 (23.2)
River/dam/spring/waterfall	10 (4.1)
Piped water/tank	2 (0.8)
Source of light	
Kerosene oil	152 (61.8)
Solar panels	51 (20.7)
Electricity	34 (13.8)
Biogas/Gobar gas	2 (0.9)
Others (other oils/candles)	3 (1.2)
None	4 (1.6)
Access to farm inputs (transport, farm, and irrigation equipment)*	
Bike/scooter	23 (9.3)
Bicycle	141 (57.3)
Bullock cart	2 (0.9)
Farm equipments (non-mechanized)	102 (41.5)
Farm equipments (mechanized)	2 (0.8)
Irrigation motor pump	6 (2.4)
PDS Ration card	
Yellow (AAY)	153 (62.2)
Red (BPL)	40 (16.3)
Don't have	53 (21.5)
PDS Utilization	
Full entitled ration	29 (15.02)
Partial ration^	164 (84.9)
Access to Anganwadi services by children	
Everyday	90 (36.7)
3 or more than 3 times a week	42 (17.1)
< 3 times a week	52 (21.2)
Never	61 (24.7)
Access to Mid-day meal services	
Everyday	115 (46.9)
3 or more than 3 times a week	45 (18.4)
< 3 times a week	46 (18.8)
Never	13 (5.3)
Not Applicable	26 (10.6)
Literacy level of HOH	
No formal education	122 (49.7)
Less than primary (till 4th standard)	22 (8.9)
Primary but less than secondary (till 9th standard)	80 (32.5)
Secondary (10th standard) & above	22 (8.9)
Occupation of HOH	
Settled Agriculture/ Shifting cultivation	192 (78.1)
Daily wager (agriculture & non-agriculture)	37 (15.1)
Hunter/Gatherer	5 (2)
Craftsmen/artisans/ Service (Government and Private)/Self-employed	9 (3.6)
Unemployed	11 (1.2)
Number of main meals consumed	
1 meal	26 (10.6)
2 meals	153 (62.2)
3 meals	66 (26.8)
>3 meals	1 (0.4)
Consumption of outside meals	
Yes	136 (55.3)
No	110 (44.7)
Number of times family eats outside meals	
Everyday	12 (4.9)
More than 3 times a week	17 (6.9)
2–3 times a week	26 (10.6)
Once a week	14 (5.7)
Once in a fortnight	4 (1.6)
Once in a month	20 (8.1)
Sometimes	43 (17.5)
Type of outside meals consumed*	
Freshly prepared meals	126 (92.6)
Ready-to-eat meals	114 (83.8)
Convenience packaged foods	127 (92.6)
Non-perishable sweets	122 (89.7)
Perishable sweets	123 (90.4)
FADI Score (Mean ± SD)	0.21 ± 0.15

(Continued)

**Multiple responses captured; percentages do not total 100%.*
^Either limited food commodities or all food commodities but in inadequate amounts.
PDS, Public Distribution System; HH, Households; HOH, Head of the household; FADI, Food Accessed Diversity Index.

counts and percentages. Quantitative analysis was performed in Stata version 15.

Ethics Approval

The study was conducted according to guidelines laid down in Declaration of Helsinki (The World Medical Association-WMA Declaration of Helsinki, and Ethical Principles for Medical Research Involving Human Subjects, 2018), and all procedures involving humans in this study were approved by the Institutional Ethics Committee at Indian Institute of Public Health-Delhi, Public Health Foundation of India and All India Institute of Medical Sciences, New Delhi. Administrative approvals from authorities at district level as well as cluster level consent from the village leader were obtained. Literate FGD participants provided written informed consent while third-party witnessed verbal consents were taken from those who were illiterate.

RESULTS

Household Characteristics, Food Production, and Access of Sauria Paharia Community

The HH survey revealed that Sauria Paharias are mainly smallholder subsistence farmers, who usually have poor living conditions in terms of housing, access to clean cooking fuel, electricity, transport facilities and poor literacy (**Table 2**). Most HHs (96%) practice settled agriculture and shifting cultivation/*Kurwa* farming (utilization of small patches of forest lands for slash and burn cultivation), while about a third of the HHs utilize their backyards as kitchen gardens (*Bari*). The majority of the HHs (60%) manage livestock like cows (mostly for draft power), raise goats, pigs, and do poultry farming; while almost all HHs reported accessing local forests, water bodies and surrounding areas for collecting indigenous varieties of foods for consumption (**Figure 3**). The community also accesses government food supplementation programs such as the Integrated Child Development Services and Mid-Day Meal Scheme [Integrated Child Development Services Scheme, 2009, Mid Day Meal Scheme Ministry of Education, Government of India] as well as national food security schemes [Public Distribution System (PDS), that provides staple food grains (wheat and rice) and other commodities such as sugar, salt etc. at subsidized prices to poor HHs] (The Public Distribution System, 2019).

Climate Variability and Its Impacts on Agroforestry Systems and Dietary Diversity

Based on the thematic analysis of the qualitative inquiries on community's perceptions along with quantitative data from HH and agricultural surveys, we explored the interconnected pathways through which climate variability impacted the agricultural production, HH dietary diversity, and food consumption patterns. We also identified certain adaptive strategies employed by the community to cope with these changes. These perceived impacts and the adaptive strategies were then assembled as pathways of climate impact on agroforestry systems and dietary diversity (**Figure 4**). Each of the steps of this figure is a compilation of the different themes that emerged from our analysis. These were then triangulated with the findings from quantitative surveys. The steps of this pathway include: (i) community's perceptions regarding climate variability observed in the region, (ii) the proximal impact of climate variability on agroforestry produce and diversity (iii) its distal impact leading to shift from subsistence economy to migratory unskilled labor with financial constraints, which has resulted in (iv) male migration leading to increasing burden on women, and, how this has (iv) cumulatively impacted the HH food consumption patterns and dietary diversity; and lastly (v) the adaptive strategies identified by the community to cope with climate variability and its implications. These themes are described and detailed as follows:

a) Community's Perception on Climate Variability in the Region

During the FGDs, the respondents reported changes in the local weather pattern which manifested as declining rainfall trends over the past two decades as well as irregular rainfall followed by long dry spells. Some also reported witnessing strong wind and thunderstorms during the monsoon season. As shared by one respondent: "*Water which used to fall (in rain), was sufficient, but now it doesn't rain that much, and even if it rains, it rains in the wrong season, it comes with lightning and in fact the rain is less and lightning is more*" (Respondent number 2, female, study village two, Sunderpahari block), while another respondent

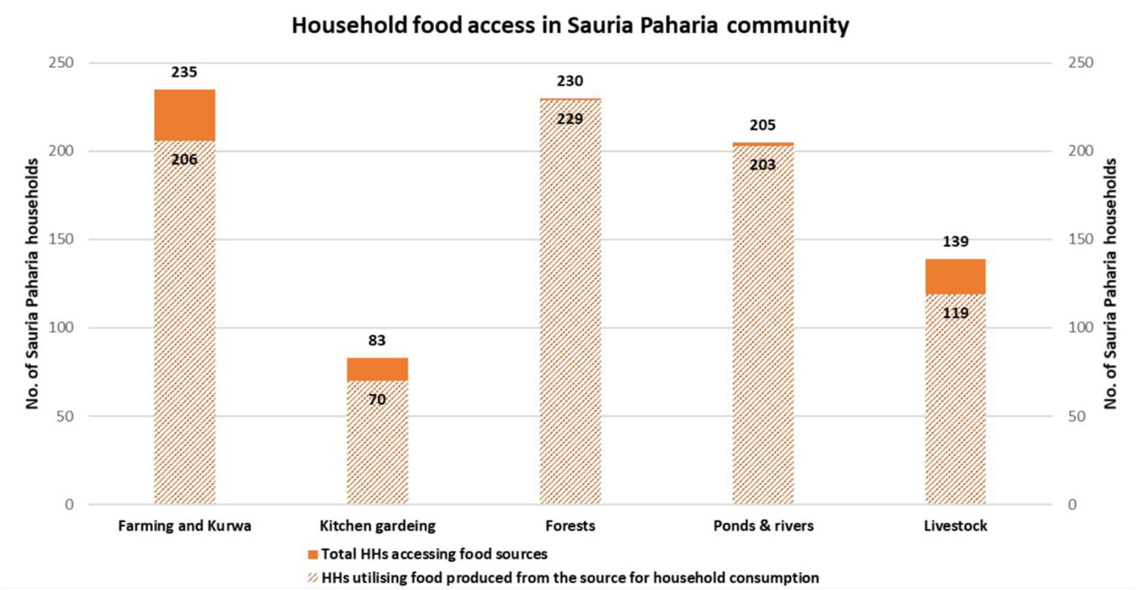

FIGURE 3 | Household food access from natural sources in Sauria Paharia community ($n = 246$). *Kurwa refers to utilization of small patches of forest lands for slash and burn cultivation.

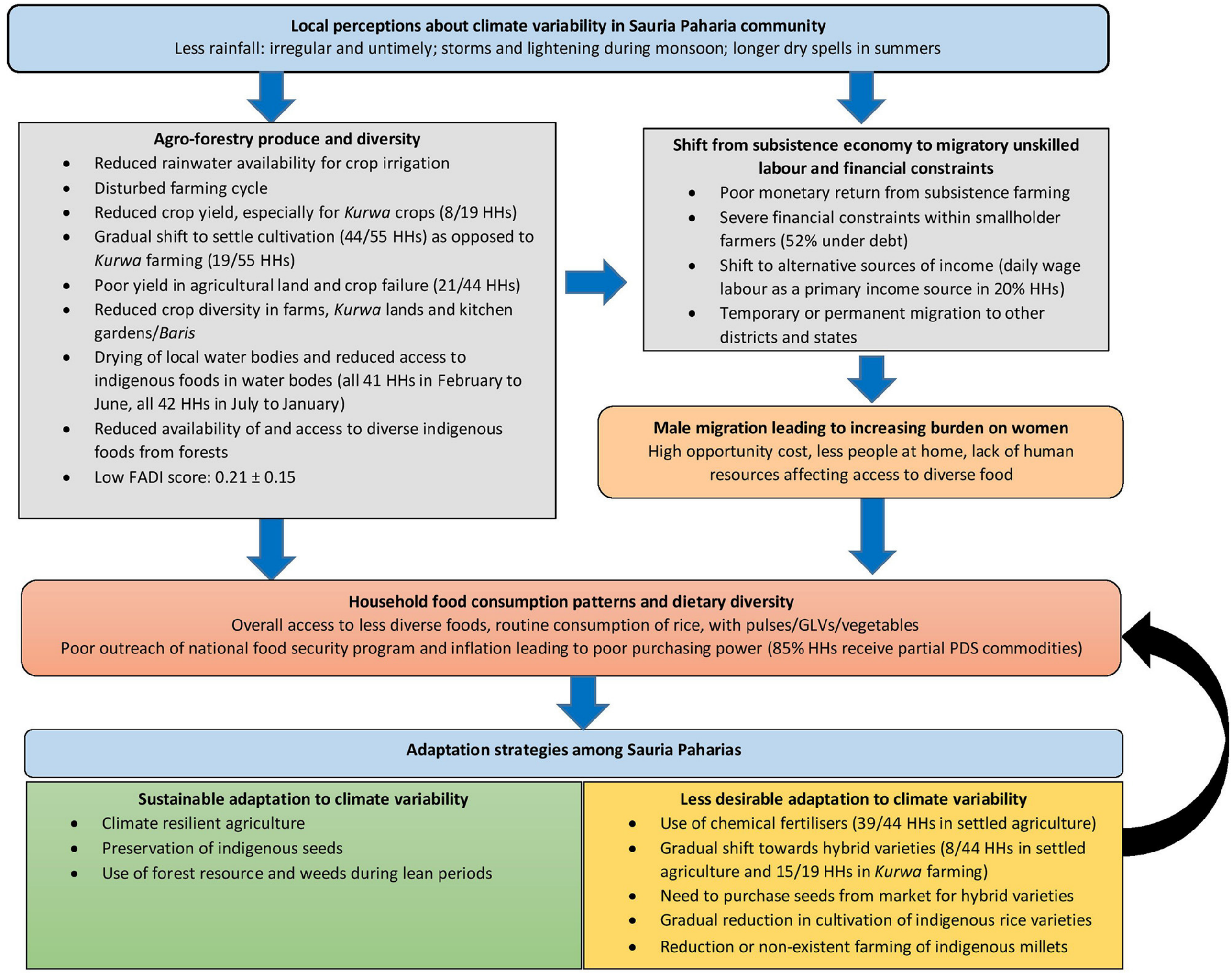

FIGURE 4 | Interconnected pathways of climate change impact on agroforestry systems, food consumption patterns, and dietary diversity among Sauria Paharias, Jharkhand, India.

stated: *"There is very less rainfall now, because of that there is drought in the village"* (Respondent number 1, male, study village two, Boarijor Block).

b) Proximal Impact of Climate Variability on Agroforestry Produce and Diversity

According to FGD respondents, variations in local weather conditions are impacting their agricultural practices and kitchen garden produce. Water scarcity has reportedly become a major issue in the region due to long dry spells. Residing in isolated hilly regions with limited access to man-made water resources, the community mainly relies on natural sources like rain, mountain springs and wells for water. However, owing to the climatic variability, the respondents reported that most natural water resources usually dry up resulting in severe water scarcity, especially during the summers. The respondents further reported an inordinate reliance on rain-fed agriculture due to financial constraints preventing access to mechanized farm irrigation systems. Hence, they felt that anomalies in usual rainfall patterns have led to reduced productivity in their farms and kitchen gardens, along with crop failure in forest lands. They also highlighted the impact of untimely and delayed monsoon on their cropping cycle and yield due to disruption of sowing and germination cycles. One of the respondents shared, *"In the earlier times we used to have timely rain, so the crops would also grow on time. Now what happens is, at times it rains, at times its sunny"* (Respondent number 3, male, study village six, Sunderpahari block).

Reduced agricultural yields were reported for indigenous varieties of cow pea (*Ghangra*), pearl millet (*Shishua*), and red gram (*Rehad*) resulting in their reduced cultivation. Respondents from some villages (in Sunderpahari block) reported that *Kurwa* farming, which was a common practice previously, has now been replaced with farming in plains, which has affected the crop diversity. The current varieties of crops grown are reportedly restricted to paddy varieties only, although historically, a diverse range of indigenous crops like finger millet (*Mandua*) and little millet (*Gondli)* were grown. One respondent said: *"If there* *is rainfall, then proper farming is there. If we get any source of irrigation then we can plant tomato, ladyfinger, and others. Because of low rainfall, soil dries, there is no source of irrigation, that is why, we have one crop only and the entire year goes by like this"* (Respondent number 10, male, study village five, Boarijor Block).

Information from agricultural surveys revealed that most of the HHs mainly practice farming during July to January, with the local monsoon season falling between June and September. Among 55 HHs that were interviewed during the main cropping cycle, a total of 44 HHs reported practicing paddy cultivation on plain farmlands and 19 HHs practiced *Kurwa* farming around the months of November-January, wherein they cultivated crops like pearl millet, cowpea (*Ghangra*), maize (*Makai*), and rice bean (*Suthro*). Respondents experienced reduced yields of these crops and attributed it to insufficient or erratic patterns of rainfall in the region. Almost all HHs grew foods in kitchen gardens or *Baris,* although majority of the HHs grew two types of crops (usually maize and mustard leaves) while more than a third practiced mono-crop cultivation (**Figures 5A,B**).

During the FGDs, the community reported historical use of a wide variety of indigenous foods from forests and local water bodies. However, a decrease in the availability of these foods was reported in the present times, which was attributed to climate variability. At present, indigenous varieties of fruits, mushrooms and leafy vegetables are accessed from wild food environment, but their availability has reportedly reduced over the past two decades. Indigenous fishes, that used to be frequently consumed in the past, have now become difficult to access, due to drying of rivers, lakes, and ponds. The community reported that water scarcity has resulted in considerable hardships to fulfill basic necessities of life like potable water for drinking and

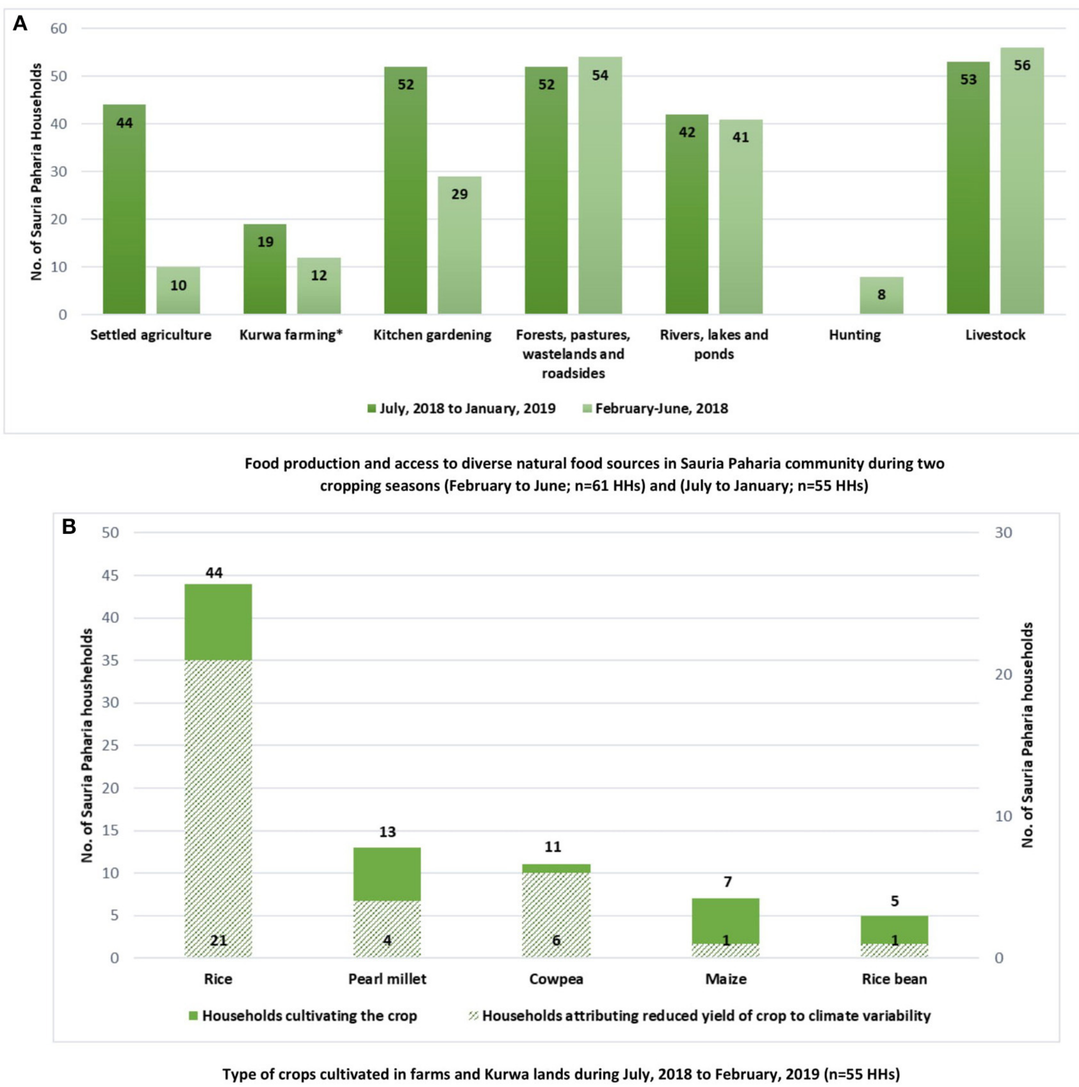

FIGURE 5 | (A,B) Agroforestry production and diversity in Sauria Paharia community, Jharkhand, India. *Kurwa farming refers to utilization of small patches of forest lands for slash and burn cultivation.

cooking and water for other purposes like bathing, cleaning, etc. One of the respondents commented: *"There is no water in the river also, which used to be there in olden days. For 10–15 years, there has been a shortage of water here. Earlier there were small streams which had water all the year round. These days everything has dried up. The amount of produce (in forest) has reduced as compared to earlier days, because of this change in weather"* (Respondent number 3, female, study village four, Boarijor Block).

The data collected in the agricultural surveys also revealed that the local forests and open spaces (pastures, wastelands, roadsides) were accessed for foods only once a week by a large majority of the HHs in the two cropping seasons (31/52 HHs in July to January and 29/54 HHs in February to June). Apart from infrequent access, only a limited number of foods (one to two varieties) were reportedly gathered by a large majority (46/52 HH in July to January; 29/54 HHs February to June). Declining availability of wild foods was reported by a few HHs (12/54 HHs in February to June) which was attributed to spoilage by pests/insects (5/12 HHs). Hunting of animals was very rarely practiced in both the seasons. During both the agricultural survey periods, all HHs reported reduced varieties of fishes in ponds, rivers and lakes, along with drying up of water sources. They attributed these toward local climate variability like reduced frequency and intensity of rainfall. In accordance with the lesser variety of foods accessed/produced despite access to diverse natural food sources like agricultural land, *Kurwa, Bari*, forest, and open access areas, the mean Food Accessed Diversity Index (FADI) for this community was also observed to be very low (**Table 2**).

c) Shift From Subsistence Economy to Migratory Unskilled Wage Laboring and Financial Constraints

According to the FGD respondents, the impact of climate variability on local agricultural practices has resulted in several social and economic outcomes. The diminishing agricultural yield has resulted in reduced availability of food for consumption and has impacted the monetary benefits gained by the HHs through selling of surplus produce in the local market or to middlemen. This has led to severe financial constraints leading to hardships and difficulty in managing basic HH expenses. For instance, a respondent shared: *"We usually sell suthri (an indigenous pulse) for our household income. But, when there is need for more money, we sell all crops produced by us during the year. We do not keep anything for household consumption. Though this should not be practiced but we feel helpless during hard times and are forced to sell these"* (Respondent number 5, female, study village four, Sunderpahari Block). During the HH survey, about one-third of the respondents reported facing an outstanding debt which was attributed to reduced income from agriculture (52%). The qualitative enquires revealed that the community has started adopting alternative sources of livelihood and is gradually shifting to agricultural and daily wage labor, construction work, and firewood collection in order to address this HH financial hardship. These findings are further corroborated with the HH survey data, which also revealed that wage laboring is the primary source of income in 20% HHs and secondary source of income in 28% HHs.

d) Male Migration Leading to Increasing Burden on Women

During the FGDs, the respondents informed that usually, the male head of the HH or other adult male member and sometimes the entire family temporarily migrates in search of work to other districts of Jharkhand or states like Maharashtra, Gujarat, Haryana, West Bengal, and the National Capital Territory of Delhi. In the absence of male members of the family, the adult women usually take charge of the farming activities in addition to carrying out usual HH chores, managing livestock and rearing of children. The crop yield and forest sojourns for collection of foods and items like firewood etc. are also affected as women can devote less time for these activities. In other words, the opportunity cost of accessing forest items along with the management of farms has increased; thus, negatively impacting the diversity of cultivated and wild food sources. One respondent noted: *"Effect of migration on our farming exists. At night, we need to take care of our farms. In the night, wild pigs come and eat up all the grains that are there. In the daytime, monkeys come and eat our crops. The men migrate, women are already doing their household chores, as a result we face loss of crops"* (Respondent number 1, female, study village one, Boarijor Block).

e) Cumulative Impact on Household Food Consumption Pattern and Dietary Diversity

During the qualitative enquiries, it was reiterated that climate variability, apart from affecting agroforestry and livelihood patterns, have further led to poor availability of and accessibility to diverse foods including indigenous varieties. This has indirectly affected the HH food consumption patterns and dietary diversity of the community. The community expressed that owing to a decline in crop productivity, suboptimal use of kitchen gardens and forest degradation, the farm and forest produce are insufficient and less diverse to meet the HH's needs. For instance, a respondent shared: *"Climate change is affecting our farm produce. If the farm produce is less, then less food is available for household consumption"* (Respondent number 5, female, study village two, Sunderpahari Block).

A significant dependence on food commodities like rice, wheat, sugar etc. distributed through PDS at subsidized prices, was reported. However, owing to supply chain issues and erratic outreach of the program, it was considered inadequate to support the food security needs. One respondent commented: *"Though we get rice (distributed under PDS), it's too less, we eat that for a few days, but for how long will it suffice. We are feeding the family, if 30 kg has been given, for how long will it suffice. In 10–15 days, it will be finished. We get ration only once in 2 months, sometimes in 6 months"* (Respondent number 2, male, study village four, Boarijor Block). **Table 2** on the HH survey data also shows that large majority of HHs (85%) receive only partial amounts and kinds of food commodities through PDS.

During the FGDs, the respondents indicated that local markets are routinely accessed to meet food requirements for the families. However, owing to general inflation in food prices, many food items (such as rice) have become expensive, thereby lowering their purchasing capacity. One respondent claimed: *"The rice which we used to eat at Rs. 14 (0.19 USD) per kg, are now* *sold at a rate of Rs. 25–26 (0.33–0.35 USD) per kg*" (Respondent number 1, male, study village four, Boarijor Block). All these challenges have resulted in scarcity of food and several HHs are unable to eat two square meals a day. A respondent commented: "*We do not have enough crop, enough land, there is nothing to eat all the year round in our house. There are only 1–2 people who can eat all the year round, there is no assurance that if we can arrange for food today, we will be able to arrange food for tomorrow also. There is nothing to feed our children throughout the year. Kota (PDS) rice is given by government so somehow we are managing otherwise the rice from market has become very expensive*" (Respondent number 2, male, study village five, Sunderpahari Block).

The qualitative inquiries further revealed that the diets historically consumed by the community (about two decades ago) usually comprised of indigenous rice, vegetables, and roots and tubers, which were flavorsome and provided nourishment and satiety. However, presently the community depends on a predominantly cereal based diet, consisting of rice with small amounts of pulses, roots, and tubers (potatoes) and/or green leafy vegetables. Respondents felt that this shift in dietary patterns has drastically compromised the nutritional quality of their meals. They further reiterated the impact of changing climate on diminishing availability of indigenous foods presently, which were abundantly available historically. As shared by a respondent: *"The indigenous varieties are tasty and provide strength. If we consume hybrid, we digest it rapidly and feel hungry again. If we eat indigenous food, we feel full for a longer duration"* (Respondent number 7, female, study village four, Sunderpahari Block).

The diet diversity assessed by exploring the food consumption data at the HH level using the FFQ [for the monsoon season, ($n = 120$)] also revealed routine consumption of cereals (mostly rice), other vegetables and roots and tubers (**Table 3**). Once a week consumption was observed for pulses, flesh foods and leafy vegetables in only half of the HHs. Seasonal fruits like mango and dates were reportedly consumed daily in about one-fourth of HHs. Milk and milk products were rarely consumed, with only 17% of HHs reporting once or twice a month consumption of cow or buffalo milk. Routine consumption of market-procured packaged and freshly prepared foods (like sweets, biscuits and savory snacks) were reported in about 32% HHs, while one-fourth HHs reported once or twice a week consumption.

f) Adaptation Strategies of the Community Toward Climatic Variability and Change

The community highlighted that climate variability, including erratic rains and dry spells, has significantly affected their nutritional, social and economic well-being. In view of these changes, they shared several strategies that they have adopted to cope with the changing climatic conditions. While some of these strategies may have beneficial environmental impact, certain adaptation strategies could pose threats to the historically evidenced sustainable methods of farming and food collection.

There are three main ways in which smallholder farmers reported adapting to climate variability: (1) utilization of traditional ecological knowledge for retaining use of climate resilient (drought tolerant) and less resource intensive indigenous varieties of crops like rice (*Bhadai Dhan* and *Swarna Dhan*), pearl millet, horse gram (*Kulthi*) and cow pea. In addition to this, indigenous seeds are also preserved using traditional methods like sun-drying the seeds and wrapping them in medicinal indigenous Sinduar leaves (*Chilo Ghasi*) to store for use in the next sowing cycle; (2) reliance on forests during lean periods to access indigenous roots and tubers (e.g., *Nappe*, Sweet potato/*Shakarkand*), wild fruits (Marking nut/*Kero, Kend,* and *Dumari*), green leafy vegetables (Koinar leaves) that grow in adverse climatic conditions; and (3) incorporation of modern farming techniques such as the use of hybrid seed varieties and chemical fertilizer for better crop productivity.

The qualitative enquiries further revealed that the practice of adopting modern approaches to farming has been met with mixed views from the community owing to its financial

TABLE 3 | Frequency of food group consumption at household level ($n = 120$) during monsoon season, in Sauria Paharia community of Jharkhand, India.

Food group	Frequency of consumption*, n (%)					
	Daily (2 or more times)	Daily (1 time)	3–6 days a week	1–2 days a week	Once or twice a month	Never
Cereals and millets	**94 (78.3)**	17 (14.2)	8 (6.7)	1 (0.8)	–	–
Pulses	6 (5)	10 (8.3)	30 (25)	**63 (52.5)**	10 (8.3)	1 (0.8)
Green leafy vegetables	3 (2.5)	10 (8.3)	24 (20)	**56 (46.7)**	26 (21.7)	1 (0.8)
Other vegetables	**98 (81.7)**	19 (15.8)	3 (2.5)	–	–	–
Roots and tubers	**106 (88.3)**	12 (10)	2 (1.7)	–	–	–
Fruits	24 (20)	29 (24.2)	**30 (25)**	24 (20)	10 (8.3)	3 (2.5)
Milk and milk products	1 (0.8)	4 (3.3)	7 (5.8)	8 (6.7)	21 (17.5)	**79 (65.9)**
Meat, fish and poultry	4 (3.3)	1 (0.8)	19 (15.8)	**65 (54.4)**	30 (25)	1 (0.8)
Mushrooms	1 (0.8)	–	9 (7.5)	40 (33.3)	**54 (45)**	16 (13.3)
Oils and fats	**106 (88.3)**	10 (8.3)	1 (0.8)	–	–	3 (2.5)
Sugar	24 (20)	**38 (31.7)**	29 (24.2)	13 (10.8)	7 (5.8)	9 (7.5)
Market procured packaged and freshly prepared foods	21 (17.5)	**38 (31.7)**	31 (25.8)	30 (25)	–	–

Figures in bold indicate most frequent consumption.
**Some food frequency categories have been merged for easy readability.*

implications as well as the issues around organoleptic quality (taste) of the crops produced. The respondents stated that the indigenous rice varieties (such as *Bismunia* and *Dumarkani*), which were consumed by the older generations for their flavorsome taste, have now become almost non-existent or extinct. The respondents also shared their views on the farming of traditional coarse millets, highlighting that their cultivation has drastically reduced due to poor yields in *Kurwa* lands and the community's adaptive strategy of switching to paddy cultivation in plain agricultural lands. On further enquiries, the respondents stated that these practices have been reinforced by the agricultural policies and local agricultural extension organizations which have been promoting high yield hybrid varieties with a primary focus on better yield. Consequently, many indigenous varieties of rice (like *Bahiar Dhan and Lal Dhan*) and maize (*Potio Makai)* have now been replaced with their hybrid counterparts. Likewise, millets like (*Gundli* or little millet), earlier consumed ubiquitously, have presently become virtually extinct. All these adaptations have also led to financial implications (purchasing of hybrid seeds, fertilizers for cultivation), which is further pushing the community into a vicious cycle of food insecurity. Though the community values its traditional practices, it has forcibly adapted these practices from a sheer survival perspective. One respondent said: *"Lal dhan (indigenous variety of rice) used to be the major crop here. After cooking, its aroma spreads even outside the house. Six to seven years back, we used to sow only this paddy, but now it does not grow. Before harvesting, all the water dries up, so paddy does not grow well. That is why hybrid rice is sown. Whether water is there or not, the yield is good, but it is not tasty*" (Respondent number 5, male, study village one, Boarijor Block).

A similar shift toward modern farming techniques were reported in the agricultural survey. During the main cropping cycle, although most HHs (36/44) reported cultivating indigenous rice varieties (i.e., *Swarna* rice), a few HHs (8/44) reported utilizing hybrid paddy seeds. In case of *Kurwa* farming, all HHs reported growing hybrid maize and cow pea, while in case of crops like pearl millet and rice bean, only indigenous seeds were used. Use of chemical fertilizers was reported by most HHs (39/44) in settled agriculture, and for *Kurwa* farming, only one HH reported the use of fertilizers while the rest (18 HHs) used neither organic manure nor fertilizers.

DISCUSSION

This paper examines the perceived impacts of climate variability among smallholder subsistence farmers of the Sauria Paharia community. These findings are further triangulated with quantitative estimates on agricultural diversity and food consumption patterns at HH level. Based on our qualitative inquiries, it was ascertained that climate variability has led to water scarcity in the region, affecting agroforestry production and diversity. This has a cascading effect and amplifies uncertainties around livelihoods, financial and manpower constraints, and impacts HH food consumption pattern and dietary diversity. Coping strategies to address these interlinked uncertainties included the retention of climate resilient indigenous varieties of crops, use of foods from natural vegetation and forests in lean periods and adoption of modern farming practices and hybrid varieties of crops. The quantitative data also provided objective estimates of diminished agroforestry and dietary diversity and attributing factors related to climate variability.

The community was found to be aware of climate variability and principally perceived it as changing rainfall patterns (both frequency and intensity) accompanied by long dry spells. Similar perceptions on climate variability have been recorded among smallholder famers across Jharkhand and other Indian states (Kelkar et al., 2008; Barua et al., 2014; Varadan and Kumar, 2014; Banerjee, 2015; Shukla et al., 2016; Ghosh-Jerath et al., 2021). The perceptions in this study coincide with the scientific data reported by the Indian Meteorological Department ("Indian Meteorological Department") and other literature suggesting an overall increasing trend in summer temperatures in Jharkhand during the last 20 years (Tirkey et al., 2018). The rainfall trend in Jharkhand also appears erratic in last 20 years with a 26–270 mm decrease in the northern region where Godda is located (Tirkey et al., 2018). Several anthropogenic elements like land use changes, deforestation and environmental degradation have been documented as possible factors contributing toward the patterns observed, especially in the state's northwestern districts like Godda (Riebsame et al., 1994; Zhou et al., 2004; Rawat and Kumar, 2015).

The community recognized that the local climate variability as long dry spells and erratic rains has affected the farm productivity and diversity (due to water stressed environment). These changes have also affected the availability of indigenous foods from natural vegetation, forests, and waterbodies in the region. The quantitative surveys also revealed similar climatic factors like erratic rainfall patterns contributing toward diminished agricultural production. The literature indicates that increasing summer temperatures may have led to water scarcity in the region (Tirkey et al., 2018), and erratic rainfall has impacted agricultural yields, especially for paddy cultivation. According to Jharkhand Action plan on climate change (2014), high rainfall (untimely rain) in rice flowering stage has caused reduced rice yield (Lal, 2001). There is also a gradual shift from rich and diverse multi-cropping patterns to intense mono-cropping (paddy cultivation) on flat lands. The agricultural survey revealed an increasing trend toward mono-cropping in the study villages, with preferential cultivation of paddy over indigenous crops like cowpea, pearl millet and rice bean. This trend is in fact being followed in the entire state of Jharkhand now. As per the recent state survey report, the total area under paddy cultivation has increased at an annual rate of 4.5 per cent, while the cultivation of pulses (red gram and black gram) have decreased at the annual rate of 0.8 per cent and 13.3 per cent, respectively (Jharkhand Economic Survey 2018-19, 2019). All these may impact the overall dietary diversity of the smallholder farmers who substantially rely on their home-grown foods.

Our findings from both qualitative and quantitative surveys have highlighted the climate impacts on the agroforestry systems, which in turn is negatively influencing the HH food availability and access. This includes foods procured from cultivated and wild sources as well as foods purchased from local markets (through indirect impact on purchasing capacity). A poor FADI score was also reported, which indicates poor diversity in terms of HH food access and production. The low FADI scores were further reflected in the consumption patterns at the HH level, with dominance of cereals (particularly rice) in a typical HH diet. The community also reported a shift from a historically diverse diet to a monotonous diet at present. Another study among Sauria Paharias revealed decreased HH access to foods collected from forests, farms and water bodies, which has resulted in reduced consumption of indigenous varieties of maize, millets, leafy vegetables and flesh foods (Mishra, 2017). Studies have also documented widespread prevalence of food insecurity among other tribal communities of Jharkhand as well as across different tribal settlements in the country (Tagade, 2012; Ghosh-Jerath et al., 2016; Chyne et al., 2017; Yasmin et al., 2018; Sharma, 2019).

Owing to diminished yield and reduced farm generated income, a shift from a subsistence economy to migratory unskilled wage laboring was reported. Migration among the smallholder farmers and tribal communities have been documented from other parts of the state as well as other states of India (Mungreiphy and Kapoor, 2010; Vermeulen et al., 2012; Das and Das, 2014; Bharali et al., 2017; Chandra and Paswan, 2020). A comparison between Census data from 2001 and 2011 shows that the proportion of ethnic groups engaged in agriculture has reduced by more than 10%, while the proportion of tribal wage laborers has increased by 9% (Census, 2011). Our study findings showed daily wage laboring as a significant income source in about one-fourth HHs and as a secondary income source in one-fifth HHs. This shift in occupational patterns may lead to a change in the economic status and social dynamics within a HH. With a rapid nutrition transition underway, when, even remote rural communities are not spared from its impact, an increased reliance on the market for sourcing food and other basic requirements of day to day life could lead to a shift in the composition of family diets. According to the state report on Jharkhand, climate impacts have diminished the agricultural and forest productivity of many smallholder farm communities, that has further impacted their HH food security, resulting in dietary deficiencies of fruits (69%), milk (43%), meat (35%), and food grains (14%). As a coping strategy, many vulnerable and poor communities in Jharkhand have shifted their dependence to market foods to meet their consumption needs (Government of Jharkhand, 2014). Quantitative estimates from our study further revealed routine consumption of ready-to-eat market foods, which are mostly cheap sources of energy and are rich in fat, sugar and salt. Some studies have also reported increasing consumption of processed foods among tribal communities, due to their changing occupational patterns (Mungreiphy and Kapoor, 2010; Barbhuiya and Das, 2014; Das and Das, 2014; Bharali et al., 2017; Ghosh-Jerath et al., 2021). The challenge of managing farms and accessing forests for wild foods when male members migrated to towns and cities was highlighted in the study. The migration of an adult member of the family can thus add to the opportunity cost of accessing diverse sources of food from wild and cultivated food environment (Ghosh-Jerath et al., 2021).

Certain coping strategies reported include cultivation of hybrid varieties of crops using chemical fertilizers and promotion of non-indigenous varieties of crops for better land productivity. However, existing literature claims that hybrid crops are extremely climate sensitive while overuse of chemical fertilizers further reduces the soil fertility. Hence, over emphasis on yield over nutritional qualities may pose a threat to the self-sustainable and environment friendly attributes of the indigenous food systems and lead to several socio-ecological implications such as biodiversity loss, soil degradation, increased vulnerability to climate variability and erosion of traditional ecological knowledge (Eliazer Nelson et al., 2019).

However, we also found some effective adaptation strategies that the community used to foster climate resilience in food production and access, while preserving their natural biodiversity. These include use of climate resilient indigenous varieties of crops, seed conservation and utilization of transgenerational traditional ecological knowledge for accessing indigenous varieties of forest foods and weeds for consumption during adverse situations. This preference toward revival and cultivation of indigenous crops has a strong sustainability component, provided the community is supported and empowered with knowledge and technology to support the production and consumption of traditional foods. For instance, with the help of local NGOs and organizations, smallholder farmers in tribal regions of states of Maharashtra, Tamil Nadu, Odisha, Karnataka and Uttarakhand have successfully revived the cultivation of indigenous crops with special focus on minor millets, thus improving their income and strengthening their food and nutrition security (Fanzo et al., 2013; Bose, 2017). Similarly, agrarian tribal communities from Madhya Pradesh and Chhattisgarh are returning to their traditional crop diversification methods which are cost-effective and give an assured yield in both low and excess rainfall conditions (Mahapatra, 2018; Mahapastra, 2020).

Study Limitations

Owing to the detailed nature of the agricultural survey and FFQ and limited time available with the respondents due to ongoing sowing season, the tools were administered on a sub sample of the study population. Although the study team had field staff speaking the local language, language and cultural barriers may have influenced some responses.

CONCLUSION

Assessment of perceptions and experiences of climate variability among Sauria Paharias and the quantitative surveys highlight the important issues concerning their food systems and livelihood patterns and suggest an urgent need to manage traditional natural resources and reduce the impacts of climate uncertainties. A significant continuing decrease in availability of locally sourced indigenous foods and erosion of indigenous seed varieties appears to be underway with serious implications on agroforestry, dietary diversity and diet quality. Our data also provides important insights into the sustainable adaptation practices used by the community, that have the potential to improve agricultural outcomes and food security by improving farm resilience, income and diet diversity, preserving the natural ecosystems and providing genetic resources for future climate adaptations. These sustainable adaptation strategies need to be supported by policies, programs and behavior change communication interventions that build on the strengths of indigenous food systems and promote climate-smart and genetically diverse agriculture for improved food, nutrition, and livelihood security of this population. While indigenous smallholder farmers covered in the present study are vulnerable to climate variability, they may also provide critical information that can be utilized to plan interventions for making current agricultural systems sustainable and climate resilient.

DATA AVAILABILITY STATEMENT

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

ETHICS STATEMENT

The studies involving human participants were reviewed and approved by Institutional Ethics Committee at Indian Institute of Public Health-Delhi, Public Health Foundation of India and All India Institute of Medical Sciences, New Delhi, India. Written informed consent was obtained from all participants who were literate. Third-party witnessed verbal consents were obtained from illiterate participants.

AUTHOR CONTRIBUTIONS

SG-J and AS conceived and designed the study with overall supervision from JF. SG-J, SD, RK, and AS supervised the entire data collection process. RK and UG did the data analysis. SG-J, RK, and UG prepared the first draft of the manuscript. AS, SD, and JF critiqued and modified the draft. SG-J had final responsibility for the decision to submit for publication. All authors read and approved the final version.

FUNDING

This work was supported by the DBT/Wellcome Trust India Alliance Fellowship (https://www.indiaalliance.org/) (IA/CPHI/16/1/502639) awarded to SG-J.

ACKNOWLEDGMENTS

We would like to express our gratitude toward the invaluable support of staff at Ekjut, a grassroots NGO in Jharkhand, especially the support of Mr. Mohd Sarfraz Ali. We would also like to acknowledge the support provided by Ms. Kiran Kumari Pasi, Deputy Commissioner Godda District, Jharkhand who facilitated necessary permission to conduct the study. We are thankful to Dr. R. D. Paswan, Civil Surgeon Godda for granting permission to conduct the study. We would like to acknowledge the contribution of Dr. Ravi Shankar at the Krishi Vigyan Kendra, Godda, for his inputs on local habitat and plant species in the region. We would also like to thank field staff, ASHAs, and Anganwadi workers in the study villages for extending their warmth and cooperation that has made this study a great learning experience. The guidance from Drs. Andrew Jones and Danny Hunter through sharing of their knowledge and expertise in food systems, sustainable agriculture and climate change is greatly appreciated. Lastly, we are indebted to the Sauria Paharia families for sharing invaluable information that has enriched this manuscript.

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Conflict of Interest: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

frontiers in Sustainable Food Systems

SYSTEMATIC REVIEW
published: 26 August 2021
doi: 10.3389/fsufs.2021.715814

Carbon Smart Strategies for Enhanced Food System Resilience Under a Changing Climate

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There is an urgent need to match food production with increasing world population through identification of sustainable land management strategies. However, the struggle to achieve food security should be carried out keeping in mind the soil where the crops are grown and the environment in which the living things survive, especially under rainfed agricultural system. Rainfed agricultural ecosystem is extremely fragile, improving soil fertility and reducing greenhouse gas emission are key factors for developing sustainable agriculture. Moreover, society increasingly expects agriculture to be more sustainable, by decreasing irrigation and mineral fertilizer inputs. Increasing food production sustainably through efficient use of resources will strongly contribute to food security, sustainable agriculture development, and increased climate change resilience. This paper addresses the effects of carbon smart technologies on greenhouse gas emission, soil quality and crop productivity in rainfed agro ecological environment. This paper hypothesized that application of carbon smart technologies could improve soil physical and chemical properties to enhance GHG mitigation and crop production. Carbon smart technologies highlighted in this paper include minimum tillage, crop residue retention, agroforestry, biofuels, integrated nutrient management and land use management systems. This paper review and discusses the work done on carbon smart technologies in different agro-ecological regions so as to understand its impact from the perspectives of the soil, the crop and the environment. The impact of conservation agriculture on greenhouse gas emissions and the underlying mechanism in different agroecological environments have been discussed. A detailed case study and tremendous advancements on the strength of integration of trees and shrub as carbon smart technologies in improving soil and crop productivity is highlighted immensely. The paper concludes with recommendations for encouraging and improving adoption by smallholder farmers to ensure more efficient and sustainable food system. This systematic review will primarily contribute to the achievement of the following Sustainable Development Goals (SDGs), particularly SDG1 (No poverty), SDG2 (Zero hunger), SDG5 (Gender equality) and SDG13 (Climate action).

Keywords: carbon, climate change, food system, nutrient, resilience

OPEN ACCESS

Edited by:
Abiodun Ogundeji, University of the Free State, South Africa

Reviewed by:
Yonas Bahta, University of the Free State, South Africa
Temitope Oluwaseun Ojo, Obafemi Awolowo University, Nigeria

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Specialty section:
This article was submitted to Climate-Smart Food Systems, a section of the journal Frontiers in Sustainable Food Systems

Received: *27 May 2021*
Accepted: *31 July 2021*
Published: *26 August 2021*

Citation:
Yeboah S, Owusu Danquah E, Oteng-Darko P, Agyeman K and Tetteh EN (2021) Carbon Smart Strategies for Enhanced Food System Resilience Under a Changing Climate. Front. Sustain. Food Syst. 5:715814. doi: 10.3389/fsufs.2021.715814

INTRODUCTION

A series of challenges face global food supply in the future, perhaps the most important of which are the combined effects of climate change and population increase. The regions where population increases are predicted to occur are those where there is the greatest food insecurity and where climate change is likely to make the situation worse (Riede et al., 2016; Lenton et al., 2019). In this region, farming systems are barely mechanized and are low input, without artificial fertilizer, plant growth regulators or pesticides, and are rainfed. Sustainable Development Goal (SDG) 2 envisages no hunger by 2030 and is perhaps one of the most difficult challenges that the world has set itself. It is also not enough to produce sufficient food, but the accessible nutritional value of the food produced must enable a healthy and active life and must be safe, as implicitly recognized in the UN definition of Food Security. Moreover, the process of producing sufficient food should not compromised on environmental quality and should be in line with efforts towards addressing SDGs 13 and 15 of climate action and life on land respectively. Yet, in many regions of Africa, including Ghana apart from the Green Revolution failing to have a major impact, crop production practice of moving from field to field on yearly basis in search of fertile soil couple with the effect of climate change would worsen the situation if innovative crop production approaches are ignored.

Climate change is negatively affecting crop production. For example, tomato yields and nutritional quality, is reducing, especially in the case of small holders that produce with minimal inputs. In West Africa, climate scenarios predict a temperature rise of up to 1.2 and 3.2°C by 2035 and 2100 respectively (Qin et al., 2014). Rainfall amounts and patterns will change with shifts in the start of the rainy seasons, most especially in the dryland areas (Adeniyi, 2016; Kim et al., 2017). Using trajectory and time series analysis of temperature anomalies and rainfall distributions for the agro-ecological zones of Ghana, there is strong evidence of local climate change across the country in diverse agro-ecological zones (Adu-Prah et al., 2019). Analysis shows local increases in temperatures for the period ranging from 0.5 to 1.0°C with varying inter-annual rainfall distributions (Adu-Prah et al., 2019) and more temperature extremes projected for the north of Ghana (Ofori-Mensah, 2017). In line with rising annual mean temperatures, the annual number of very hot days (days with daily maximum temperature greater than 35°C) is projected to rise substantially in the different agroecological zones of Ghana (Adjei and Kyerematen, 2018). Thus, projected changes in climate will pose threats to food production and food security, and hence to the livelihood of the people. Typical effects include reduced crop yield, and increased risks of crop failure (Centre for Indigenous Knowledge Organisation Development (CIKOD) Peasant Farmers Association of Ghana (PFAG), 2018). All these factors contribute to making smallholder farmers, particularly those in more ecologically fragile, risk prone agro ecological areas, more vulnerable to food and nutrition insecurity [Centre for Indigenous Knowledge Organisation Development (CIKOD) Peasant Farmers Association of Ghana (PFAG), 2018]. If care is not taken, the effort made in achieving SDG's 1 and 3 of No poverty and Good health and well-being respectively will be compromised.

Ghana's strong economic dependence on agriculture, and the sector's limited adaptive capacity underlines the country's high vulnerability to climate change, especially as <1% of the national crop area is irrigated (FAOSTAT, 2019), and crop yields depend on water availability and are susceptible to drought and heat stress. Staple crops, such as maize and rice, is traditionally rainfed, and yet are of great importance for food security. There is a risk of further intensification of these trends as climate change progresses and the demand for food increases as expected. The major food crops are predominately grown by smallholder farmers under rainfed conditions (www.worldbank.org) with low yield productivity. The low yield is primarily due to water and heat stress, but also due to declining soil fertility, and soil organic matter content; land degradation caused by reduced vegetative cover, soil and water erosion, and forest depletion (Burney et al., 2010). Fertilizer input to increase and stabilize crop yields has been increased by the launch of the Ghana's farm input subsidy programmes (FISP). However, in a recent study by Oppong et al. (2014) crop production data showed that there was no appreciable increase in the yields of the target crops; maize, rice, sorghum and millet. To a large extent, estimates of value-cost ratios suggest that fertilizer use among maize farmers in Ghana is not profitable, in some cases even under the subsidy. This situation poses a great threat to food and nutrition security of the people as well as the health of the environment. Mitigating climate change by changing agricultural practices has big potential (Adiku, 2015; Ahmed, 2016), and the mitigation potential in smallholder farming systems in the developing countries may be realized by implementing elements of climate smart agriculture (http://www.fao.org/climate-smart-agriculture/en/) and conservation agriculture (http://www.fao.org/conservation-agriculture/en/). The potential for carbon sequestration and increased carbon storage in degraded lands are particularly high and can partly be achieved by practices that also improve soil fertility e.g., application of nutrient amendments and organic substrates such as manures, bio-solids, and composts. There is therefore the need for adapting an approach that makes use of carbon smart technologies including conservation agriculture, agroforestry and other improved land used management practices.

The challenge of meeting the demand for food has received great attention worldwide. The current increases (doubled) in food production in the last four decades are due to a seven-fold increase in N fertilization (Shiferaw et al., 2013). However, the indiscriminate use of N fertilizer could result in negative effect on agriculture, socio-economic and environment such as global warming (Giles, 2005). For this reason, present concerns about agricultural and environmental sustainability have stimulated attempts to maximized crop yields while decreasing N input (Shiferaw et al., 2013). According to Snyder et al. (2009) high-yield agriculture has the potential to increase the annual input of crop residue C to soils. In this context, the ability to develop and implement innovative soil management practices plays an important role in maintaining or improving the productive capacity of soils and enhancing the resilience of the agroecosystem which is a key priority to maintain both the quality and quantity of crop production. The adoption of carbon smart technologies such as agroforestry, conservation agriculture, different land use management system and integrated nutrient management principles as part of a change in management system in combination with other sustainable soil management practices (Van den Putte et al., 2010) has been reported to increase crop productivity and carbon inputs (Huang et al., 2008; Yeboah et al., 2016). In an effort to reduce the concentrations of greenhouse gases (GHG) in the atmosphere in order to lessen the potential impacts on global climate, considerable attention has been paid to soil management practices. According to Snyder et al. (2009) cropland has the potential to reduce agricultural greenhouse gas emission by adopting improved soil management practices. Scientific soil management strategies can enhance soil quality and increase crop biomass production (Snyder et al., 2009). These strategies can be achieved by increased input of crop residues while minimizing C loses by erosion, decomposition and carbon emission. Whiles conservation agriculture systems has been noted to improve soil organic C (Andruschkewitsch et al., 2013), conventional plow based farming systems could accelerate carbon mineralization and thus reduce soil C content, which is attributed to soil aggregates disruption and increased oxidization through soil disturbances (Ussiri et al., 2009). According to Yeboah et al. (2016, 2018) conservation tillage combined with residue retention increased field pea yield by 12.5% and spring wheat yield by 14.0% vs. conventional tillage over four years of experiments. Apart from positive effects in both reducing emissions and increasing the sequestration of greenhouse gases, the application of carbon smart technologies will deliver immediate benefits. We postulate that, to counteract the obvious threat of food security and environmental degradation in sub-Saharan Africa, including Ghana, sustainable land use concepts and nature-based solutions that incorporate carbon smart technologies are urgently needed to ensure ecosystems, biodiversity and food security are preserved in the long term. Lastly, we consider future perspectives whether carbon smart technologies offers socio- economic opportunities for smallholder farmers. This paper hypothesized that application of carbon smart technologies could improve soil physical and chemical properties to enhance GHG mitigation and crop production. This proposal aligns perfectly with current national agricultural and climate change policies in SSA and with policies for agricultural developments in Ghana as described by Ministry of Food and Agriculture (http://mofa.gov.gh/site/index.php/about-us/about-the-ministry). The present systematic review presents progress towards the sustainable development goals (SDGs), particularly SDG1 "No poverty," SDG2 "Zero hunger," SDG5 "Gender equality" and SDG13 "Climate action" as it addresses the challenges of climate change for smallholder farmers in SSA.

SEARCH METHODS

The search methods were not strictly defined or focused in advance, the question for the review evolved and was refined throughout the initial phases of literature searching and data extraction. The research questions became "can carbon smart practices help in addressing problems of poor soil fertility, low crop yield, and high greenhouse gas emission?;" "which of the carbon smart practices is better in terms of improving soil and crop productivity, and maintaining environmental quality?;" "how does carbon smart practices improved soil, crop and environmental health compared to traditional cropping practices?," "at what extent can carbon smart strategies reduce greenhouse gas emissions whilst improving soil and crop productivity?". Population, Intervention, Comparison, Outcomes and Study (PICOS) design was used as a framework to formulate eligibility criteria in the systematic reviews (**Figure 1**).

As the starting point for the synthesis the databases MEDLINE (via EBSCO), CINAHL Complete (via EBSCO), were searched between November 2020 to March 2021. Five key concepts were used for the search; soil and crop productivity; greenhouse gas emission; conservation agriculture; agroforestry for soil and crop production; soil carbon sequestration.

Studies from countries with similar economic and cultural situations and levels of agriculture development were included, using the following criteria: published in English; published between 1985 and 2021 and studies in high income countries: UK, Western Europe, USA, Canada, Australia and New Zealand. The year 1985 was identified as a limit, as this coincides with the period of immense interest in sustainable agriculture.

Quality Appraisal

The criteria proposed by Dixon-Woods et al. (2006), for assessing the quality of all empirical papers for Center for Internet Security (CIS), regardless of study type, were used. These have been adapted from the National Electronic Library for the evaluation of qualitative research.

Minimum Tillage for GHG Mitigation

Soils play an important role in climate change mitigation by storing carbon and decreasing global greenhouse gas emissions in the atmosphere (Lal, 2004). However, poor soil management through unsustainable agricultural practices could release nitrous oxide (N_2O), methane (CH_4) and carbon dioxide (CO_2) into the atmosphere (IPCC, 2013). The adoption of sustainable management of soil resources aims at increasing soil quality favorable for mitigating greenhouse gas emissions (Sharma et al., 2011). The impact of carbon smart strategies on greenhouse gas emission and the mechanism causing emissions has been diverse. It is prudent that a systematic review is conducted to understand the influence of carbon smart strategies on GHG emission and the underlying mechanism in different agro ecological environments.

Rainfed N_2O Emissions

According to Saggar et al. (2010) N_2O emissions are driven by the applications of fertilizer nitrogen (N), soil tillage and crop type, with their effect dependent on soil and weather conditions. Different results have been reported regarding the influence of tillage and straw practices on N_2O flux. Some research has shown that conservation tillage, especially no–tillage, results in increased N_2O emissions relative to intensive tillage systems (Hermle et al., 2008). Increased denitrification

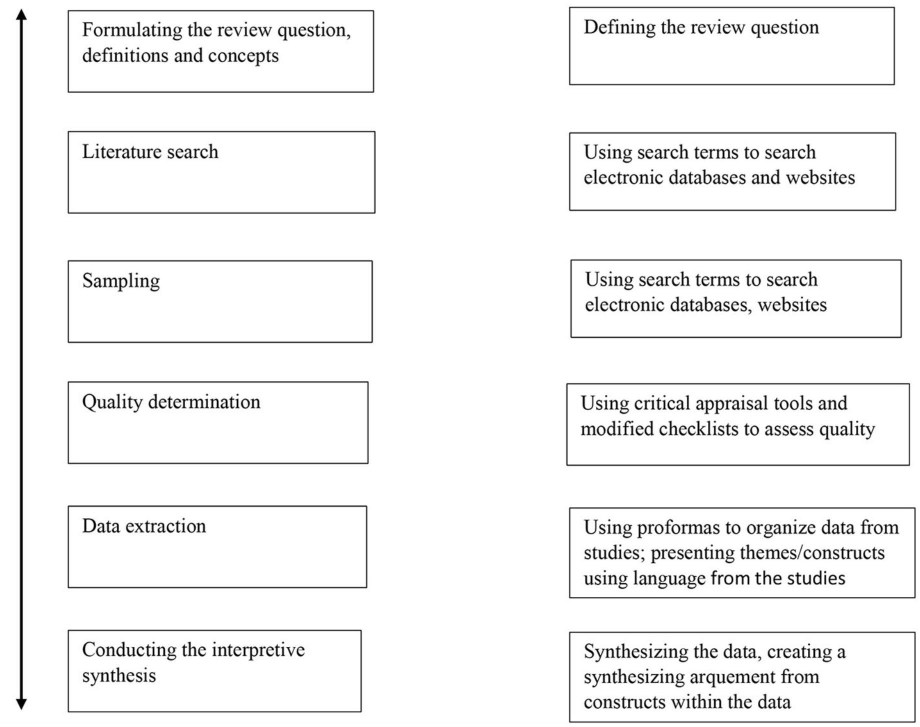

FIGURE 1 | Phases of the Critical Interpretive Synthesis.

under reduced tillage has been attributed to decreased water filled pore space and mineral nitrogen concentration (Oorts et al., 2007), reduced gas diffusivity and increased water and reduce soil bulk density content (Hermle et al., 2008). Minimum conservation tillage maintains higher soil moisture levels and surface soil organic matter than where more intensive tillage practices are used. In addition, Bhatia et al. (2010) noted that the emissions of N_2O were higher in minimum till vs. conventional till system since soils under minimum tillage were generally more moist and had organic matter concentrated near the soil surface, which favored N_2O production. Other studies have observed no difference in N_2O emissions between minimum and conventional tillage treatments (Choudhary et al., 2002). However, no–tillage system has been reported to produce less N_2O than that of conventional tillage (Duan et al., 2013). This has been attributed to conventional tillage causing more soil organic C decomposition due to higher levels of soil–residue mixing and higher soil temperatures (Duan et al., 2013). In a study conducted by Yeboah et al. (2016) reported that N_2O emissions were comparatively higher under conventional tillage treatments soils than those from no–till or minimum tillage treatments with straw retention (**Figure 2**). The low N_2O emission in the minimum tillage plots is therefore, a significant finding in this study as many other agricultural practices that are meant to limit CO_2 emission also increase N_2O emissions, which does not seem to be the case in this review.

These data are in accord with those reported by Chatskikh and Olesen (2007), but contrary to reports by Gregorich et al. (2008) who found that N_2O emissions can be higher from no-tillage when compared to conventional tillage plots. The authors attributed the decreased N_2O emission by improving soil water drainage and soil structure, as shown by soil bulk density and soil hydraulic conductivity. This result support the assertion that increasing soil carbon stock and reducing soil disturbances could help reduce N_2O emission in agricultural systems. In this regards, application of conservation agriculture practices, including minimum tillage and increased residue incorporation has a higher potential to reduce nitrous oxide emission and to promote low emission cropping system.

Rainfed CH_4 Emissions

Most previous studies indicate that conservation tillage couple with appropriate straw application acts as a net sinks for methane. However, both increased and decreased CH_4 consumption has been reported in no-till soils (Venterea et al., 2005). Changes in land use, especially cultivation of formerly undisturbed soils, strongly decrease the CH_4 oxidation and consequently the uptake of atmospheric CH_4 by the soil (Hütsch, 1998). Reduced and no-tillage practices have been proposed as alternative system for restoring the CH_4 uptake capacity of soils (Hütsch, 2001). This is because the improvement of soil quality through these practices is beneficial to methanotrophs (Hütsch, 1998, 2001). Agricultural soils exhibit both minor emitters of CH_4 to sinks for atmospheric CH_4 (Mosier et al., 2006). Agricultural soils become sinks of CH_4 when methanotrophic bacteria take up CH_4 to oxidize it for energy production (Hütsch, 1998). There is evidence that tillage reduces this oxidation in soils leading to less CH_4 removal (Hütsch, 1998). In a study by Yeboah et al. (2016), greater uptake

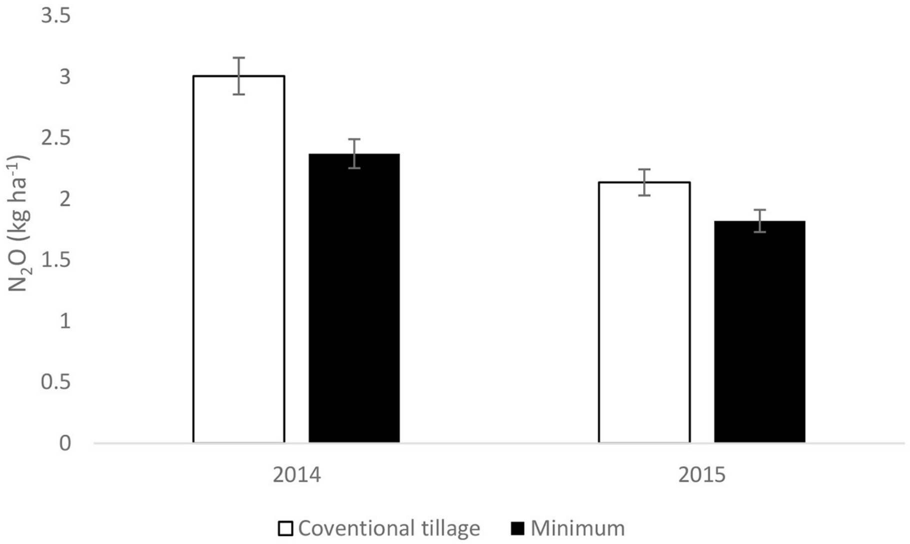

FIGURE 2 | Cumulative N_2O emissions in spring wheat as affected by conventional tillage (hollow bars) and minimum tillage (filled bars). Data re-plotted from Yeboah et al. (2016).

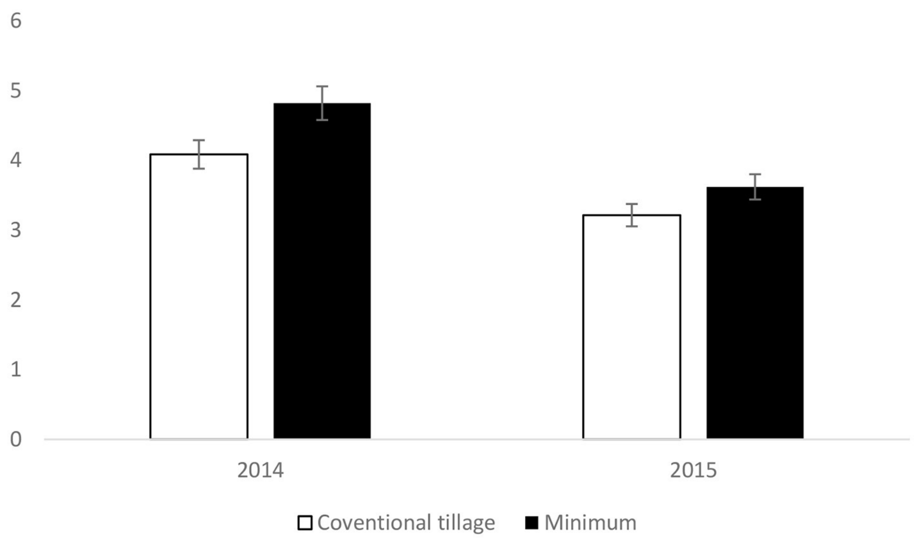

FIGURE 3 | Cumulative CH_4 emissions in spring wheat as affected by conventional tillage (hollow bars) and minimum tillage (filled bars). Data re-plotted from Yeboah et al. (2016).

of CH_4 was observed in the minimum till soils under rainfed conditions (**Figure 3**).

The greater uptake of methane in the no tillage plots, especially with straw application may be due to better aeration and less soil degradation which enhanced methanotroph activity. A well-drained soil provides ideal environment for the methanotrophs which are key bacteria in enhancing CH_4 uptake. The mulch layer on top of minimum tillage soils provided soil organic carbon and strengthened the stability of soil aggregates making them resist soil erosion caused by water and wind. When eroded soil particles do not fill pore spaces, porosity is increased and bulk density decreases. McLain and Martens (2006) noted that methanotroph activity was enhanced under adequate diffusion of gases in the niche of microbial activities. Plowing disrupts the ecological niche for methanotrophic bacteria, influence the gaseous diffusivity, and affect the rate of supply of atmospheric CH_4 (Hütsch, 1998). Straw returned in no-till system tends to increase soil C and reduce soil density, which may lead to lower risk of CH_4 emissions. Mosquera-Losada et al. (2007) reported that soil degradation can reduce the ability of soils to consume or oxidize atmospheric CH_4 by as much as 30–90%. However, Omonode et al. (2007), hold a contrary view to the

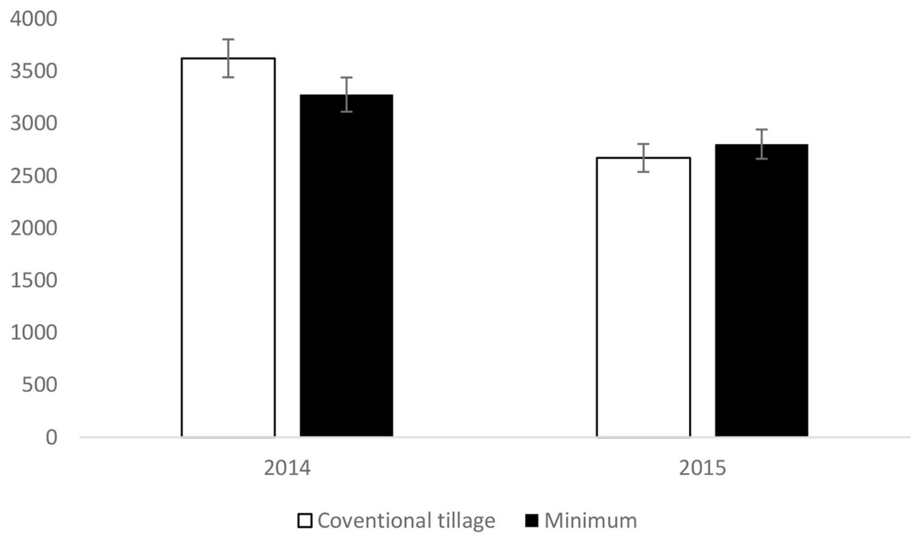

FIGURE 4 | Cumulative CO_2 emissions in spring wheat as affected by conventional tillage (hollow bars) and minimum tillage (filled bars). Data re-plotted from Yeboah et al. (2016).

above indicating that anaerobic conditions are prevalent under no-tillage and consequently lead to CH_4 emission. The high potential of conservation tillage in reducing methane emission is significant since current increases in atmospheric GHG levels require that innovative strategies are undertaken to mitigate impacts of climate change, particularly management practices capable of improving soil C sequestration.

Rainfed CO_2 Emissions

Crop residue retention is related to the increase in organic C concentration and thus reduces CO_2 emission (Zhang et al., 2013). Sequestration of C and N in soils could be achieved through adoption of conservation tillage methods and crop residue retention (Zhang et al., 2013). Minimum tillage retains more plant residue on the soil surface and has greater near–surface soil C contents than conventional tillage (Lal, 2009). The decomposition of plant residue is also slower in conservation tillage as a result of reduced soil–residue contact compared with residue that is completely incorporated by conventional tillage (Lal and Pimentel, 2009). According to Reicosky and Archer (2007) the amount of C lost in the form of CO_2 due to soil tillage practices is depended on tillage intensity volume of soil disturbed. Lower CO_2 emissions were observed in minimum tillage plots with residue (Yeboah et al., 2016, 2018) as shown in **Figure 4**.

The lower CO_2 emissions could be attributed to the significant improvement in the soil organic carbon from the residue retention, which has been reported by other researchers (Zhang et al., 2013; Wang et al., 2020; Tiefenbacher et al., 2021). There is a general consensus that no–till with straw covering on the soil surface decreases soil CO_2 emissions, as suggested by Andruschkewitsch et al. (2013), soil disturbances due to tillage increase organic matter contact with microorganism leading to rapid decomposition. Higher CO_2 emissions in conventional tillage soils, especially with residue removal was attributed to the increased surface roughness and pores that are created by soil disturbance that accelerate decomposition of SOM (Ussiri et al., 2009). The aggregates 'disruption due to tillage renders the initially protected organic matter (OM) accessible to decomposers. Higher CO_2 emissions in conventional treated soils was attributed to the increased surface roughness and voids that are created by soil disturbance that accelerate. Conservation tillage enhance residue cover on the soil surface and have greater upper surface soil C contents than conventional tillage, the decomposition of plant residue is slower in conservation tillage as a result of reduced soil–residue contact compared with residue that is completely incorporated by conventional tillage (Lal, 2009). The review has highlighted the use of minimum tillage to reduce GHG (N_2O; CO_2; CH_4) emissions resulting from agriculture practices. For smallholder famers, there is a unique advantage for encouraging the use of minimum tillage. This because it can easily fit into their farming operations since cultivation and farming operations are on small scale and normally does not involve sophisticated farm implements.

Minimum Tillage and Crop Productivity and C Balance

Previous researches have shown that conservation tillage can improve crop yields (Huang et al., 2008; Zhang et al., 2013). In a study by Yeboah et al. (2016, 2018) minimum tillage couple with straw retention soils improved wheat grain yield by 49.78% on average compared to conventional tillage system with residue removed (**Figure 5**). The differences in grain yield could be related to the improved soil quality (Huang et al., 2008; Zhang et al., 2013). A possible explanation could be that minimum tillage with residue retention promoted wheat growth

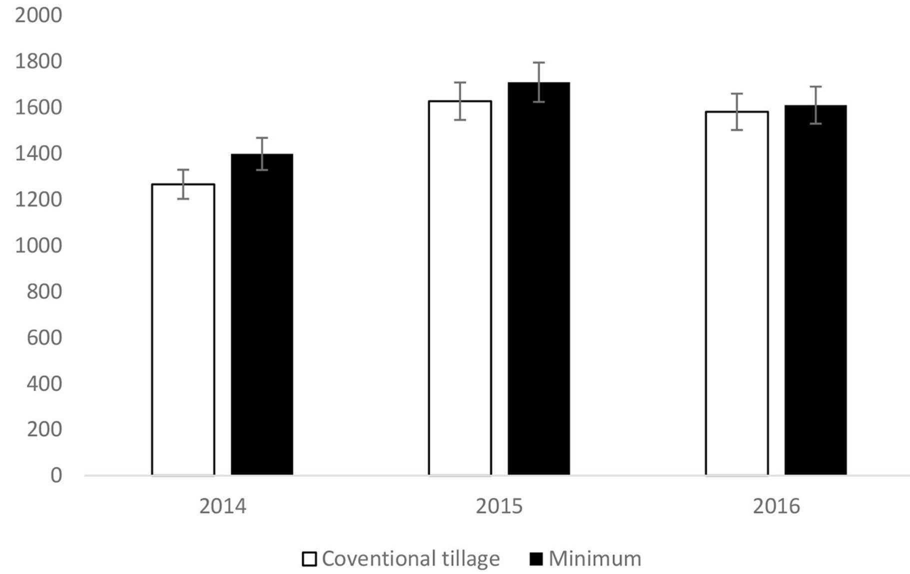

FIGURE 5 | Grain yield in spring wheat as affected by conventional tillage (hollow bars) and minimum tillage (filled bars). Data re-plotted from Yeboah et al. (2016).

by increasing soil water availability and lowering bulk density that enhance root penetration.

In the Mexican highlands improved high-yielding wheat varieties yielded double under conservation agriculture compared to the farmer practice or zero tillage with residue removal, all with the same fertilizer inputs (Govaerts et al., 2005). However, Lampurlanes et al. (2002) found no difference among tillage systems in crop yield. There was a direct and significant relation between the soil quality status of the soil and the crop yield, and no tillage with crop residue retention showed the highest crop yields as well as the highest soil quality status. In contrast, the soil under no tillage and conventional tillage with crop residue removal showed the lowest soil quality and thus produced the lowest yields. This is in line with other studies, for instance Ozpinar and Cay (2006) found that wheat grain yield was greater when tillage practices resulted in improved soil quality. Management strategies in agroecosystems may influence C balance in soil through differences in soil C input and soil C output (Ghoshal and Singh, 2010). In agricultural system when C input to the soil exceeds the C output from the soil, a positive imbalance occurs which subsequently results in C sequestration in soil (Mukherjee and Lal, 2015). Minimum tillage and straw application significantly have been noted to enhanced soil C balance (**Figure 6**).

Zhang et al. (2012) found the beneficial role of straw returned for C sequestration. When C inputs and outputs are in balance with one another, there is no net change in soil C levels. Also, straw treated plots had higher C sequestration potential in terms of soil C balance particularly that of tillage removal with residue retained plots. On the other hand, soils without carbon inputs with or without tillage treatment had negative C balanced. The increased in annual C inputs could translate into higher C storage in terms of soil C build-up and thus enhanced C sequestration.

AGROFORESTRY

Agroforestry Impact Soil Nutrients and Crop Productivity

Africa just as the whole world faces the change of feeding increasing population against limited land resources in the face of climate change. Technologies that enable improved and sustainable intensification of crop production will be a way forward. The loss of soil organic carbon (SOC) and soil nutrients especially N has been observed to be the most limiting factor of crop production in the tropics and sub-Saharan Africa (Zingore et al., 2015; Liu et al., 2021). Using a crop model Liu et al. (2021) observed that, as a result of N deficiency, the yield of yam a very important food security crop along the West African yam belt including Ghana was limited for 69, 77, 82, and 92% land area at the savannah, forest, forest-savannah transition and coastal savannah respectively of Ghana. Also, APSIM showed that lack of synchronization of sowing date of maize with optimum radiation, rainfall, and nutrients (especially N) is the cause of the huge maize yield gap in Ghana (Owusu Danquah et al., 2020). For rice production, N is the most limiting nutrient followed by Phosphorus (P). The absence of N, P, and Potassium (K) resulted in a yield reduction of 32, 16, and 11%. The study suggested N application of 56, 91, and 122 kg N ha^{-1} would result in a yield of 3, 5, and 7 t ha^{-1} respectively (Saito et al., 2019). An on-station and on-farm evaluation on cassava in Uganda and Kenya revealed poor soil fertility as one of the major limiting factors. Cassava productivity was limited as much as 6.7 t ha^{-1} compared to 5.4 and 5.0 t ha^{-1} limitations resulting from early water stress and weed management respectively (Fermont et al., 2009). The yield gap of food crops improved with the use of fertilizers and improved seeds. Also, the yield and poverty gap are directly related, and thus yield improvement would reduce

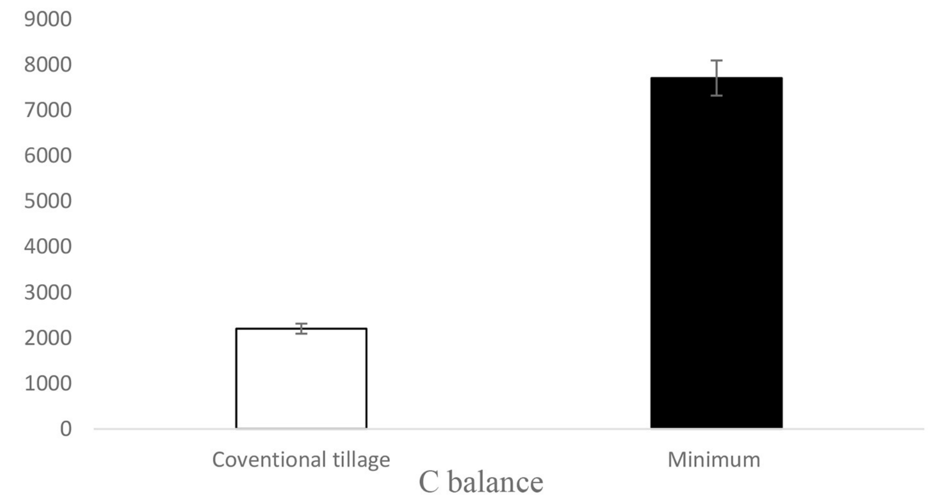

FIGURE 6 | Grain yield in spring wheat as affected by conventional tillage (hollow bars) and minimum tillage (filled bars). Data re-plotted from Yeboah et al. (2016), thesis, unpublished.

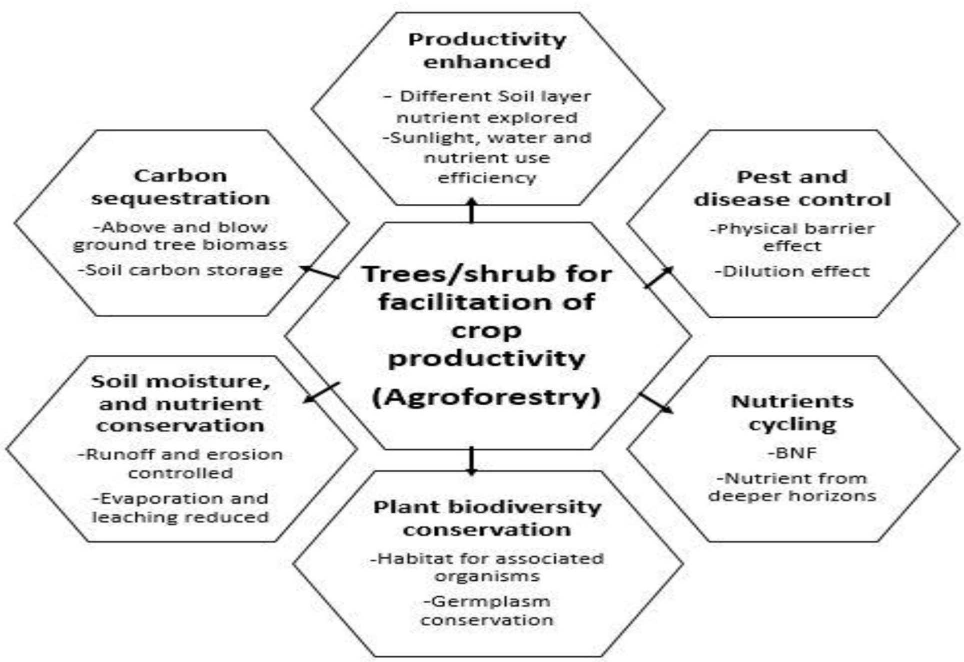

FIGURE 7 | Integration of trees and shrubs into cropping systems for facilitation of resource use and crop productivity. Source: adopted from Malézieux et al. (2009).

poverty and improve farmers' livelihoods (Dzanku et al., 2015). To ensure food security in the face of limited land resources and climate change for the increasing population calls for urgent need to address these yield limitations with improved climate smart technologies. Mueller et al. (2012) observed a high chance of meeting sustainable intensification and food security challenges if changes can be made in soil nutrition and water management. Environmental impact as results of agriculture can be minimized whiles increasing important and major cereals such as maize, wheat, and rice by 30%. This is where agroforestry can play a vital role by providing options that enable efficient and sustainable use of the resources whiles conserving them for future generations. Agroforestry is a collective name for land use practice which incorporate growing trees and shrubs with crops and or livestock so that they interact to facilitate productivity (Nair et al., 2010). This practice has recently received considerable attention as a biological strategy for carbon sequestration for mitigating greenhouse gas emissions recognized by the Kyoto Protocol.

This is because interactions between trees and shrubs used in agroforestry systems are managed to facilitate the growth of the associated food crop.

Agroforestry Facilitate Resource Use in Cropping Systems

Agroforestry practice involves the cultivation of more than one plant species on the same piece of land, at least two plant species or more. The selection of the species is very important and relies on the ecological principles of reducing competition and maximizing complementation or facilitation (Erskine et al., 2006; Rao et al., 2007). Competition is where the two or more plant species used in the agroforestry system interact in such a way that at least one exerts a negative influence on the growth and development of the other species. Whiles complementation or facilitation is where the two or more plant species used in the agroforestry system interact in such a way that it exerts a positive influence on at least one or more of the species. When all the species exert positive influence on each other it is termed mutualism (Van Noordwijk et al., 2015). However, in agroforestry systems mutualism is hardly attained. **Figure 7** shows how the presence of trees/shrubs in cropping systems facilitates resource use to the benefit of the associated food crop. Yang et al. (2020) observed that rubber tree takes more than 40% of its soil water from the shallow horizon (0–20 cm) of the soil resulting in an interspecific competition between rubber tree and their intercrop. However, the intercrop facilitated soil water to the rubber enabling it to acquire about 9–24% of its soil moisture requirement from the shallow soil horizon (0–20 cm).

Species diversity in an ecosystem is directly related to productivity and income per plant in the plant ecosystem. The income per plant increased for fruits, firewood, and timber but decreased for bananas and cocoa as diversity increases. This suggests stronger complementarity than competition between plants on the higher strata of the canopy (fruits, firewood, and timber trees) and vice versa for the plants occupying the lower canopy (Banana and Cocoa) (Salazar-Díaz and Tixier, 2019). This study has emphasized the need for the selection and arrangement of agroforestry components to achieve optimum benefits. When the management and spatial influence of tree species such as *Eucalyptus spp*., *Sesbania sesban*, *Grevillea robusta*, *Calliandra calothyrsus, Markhamia lutea*, and *Croton macrostachyus* were evaluated on water availability and productivity of maize on smallholders' farms in Kenya, it was observed maize productivity increased with leguminous species. Also, the presence of the tree species significantly influenced soil moisture distribution at the field (Nyaga et al., 2019). Moderate shading by trees in a cocoa farm resulted in improved nutrient assimilation and productivity of cocoa (Asare et al., 2017).

Using pigeonpea in cropping systems has provided readily available and rich N biomass which improved N availability and used resulting in improved crop productivity (Kermah et al., 2018; Owusu Danquah, 2020). **Figure 8A** shows the sunlight reaching yam leaves above, mid, and below the canopy along the stake. Sunlight reaching the yam leaves was influenced by the cropping system. Sunlight intensity on yam leaves at mid-canopy (MC) of PB and sole yam were similar to the sunlight intensity on the yam leaves above canopy (AC) of PA for both locations and years. Sunlight reaching the below canopy (BC) of both PB and Sole yam cropping systems was higher than the sunlight reaching the mid-canopy (MC) of PA fields. This had implications on soil moisture retention, weed control, and N use by the yam. Although the yam leaves of the yam in the PA field were shaded, this facilitated soil moisture retention, control weeds, and improved N use by the yam. **Figure 8B** shows the mean relative chlorophyll content of the yam leaves. Yam leaves on PA fields had the best leaf chlorophyll content. Farmers' practice (No fertilizer) and half recommended fertilizer rate (23–23–30 N–P_2O_5-$K_2$0 kg/ha) followed the order of PA>PB> sole yam in leaf chlorophyll content whiles the full fertilizer rate (45–45–60 N–P_2O_5-K_2O kg/ha) followed the order of PA=PB>sole yam.

Thus, the presence of the pigeonpea though shaded the yams, shading was positive, it protected the yam ridges from erosion, suppressed weeds, made N available to the yams facilitating yam productivity. As a C3 plant species, it becomes saturated upon receiving 50% of the required light intensity. High environmental temperature conditions around crops especially C3 plants increases oxygenation reaction along the photorespiratory pathway resulting in about 25–30% loss in carbon fixation (Slattery and Ort, 2019). Thus, proving some level of shading is necessary for staple food crops (root and tuber and legume food crops) which are C3 plants so as to operate under full photosynthetic potential for improved productivity (Huang et al., 2020; Owusu Danquah, 2020). In the face of climate change integrating trees into cropping systems on smallholder farmers would play a dual role of shading and conserving moisture and also provide food and income from their produce.

If the trees and shrubs used fixes N through biological nitrogen fixation (BNF) it will improve N availability. This strategy of intentionally using legumes trees and shrubs would facilitate N availability in cropping systems to reduce N inorganic fertilizer application. Since N fixation and availability to the associated crop is a factor of the biomass of the legume grown, the N per unit area fixed by tree legumes are better than major crop legumes used in cropping systems (Mthembu et al., 2018). Also, N fixation can be high when N in the medium or soil is limited (Ennin et al., 2002). Thus, it presents the opportunity to integrate tree legumes into cropping systems in sub-Saharan Africa where the soils are limited in N and other nutrients for sustainable food crop production. Owusu Danquah et al. (2017) observed that when pigeonpea (a legume tree) preceded yam cultivation, half recommended poultry manure (3 t ha^{-1}) and a third recommended fertilizer rate (15–15–20 N–P_2O_5-K_2O kg ha^{-1}) was enough for sustainable yam production on continuously cropped fields. Also, when yam was cultivated in alleys of pigeonpea and the pigeonpea biomass pruned on the soil, half the recommended fertilizer rate (23–23–30 N–P_2O_5-K_2O kg ha^{-1}) was enough for sustainable yam production on continuously cropped fields (Owusu Danquah, 2020).

Improving Productivity and Sustainable Land Use

Integration of trees and shrubs in cropping systems improves the general productivity of the cropping systems compared to their monocrop. This is because the presence of the trees and shrub makes available nutrient-rich biomass which improves

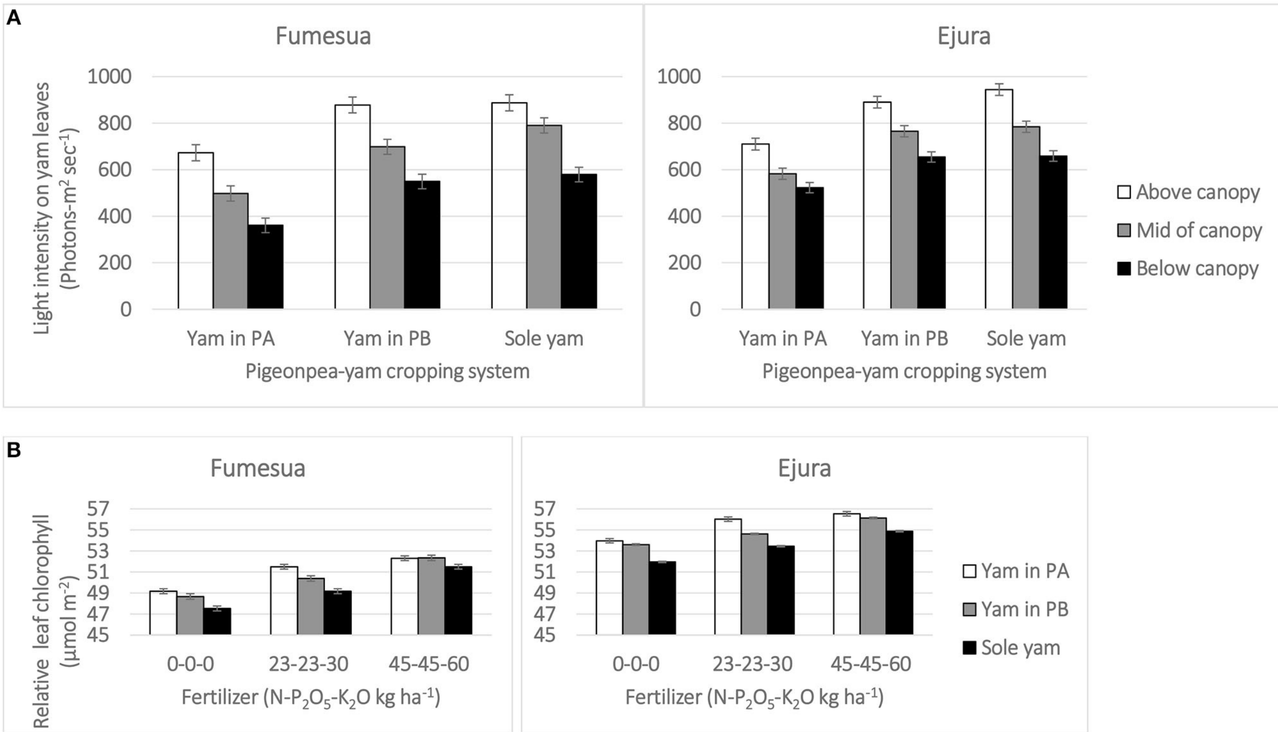

FIGURE 8 | (A) Mean biweekly sunlight photons reaching yam leaves in pigeonpea–yam cropping system. PA, Pigeonpea in alley; PB, Pigeonpea as border. Source (Owusu Danquah 2020). **(B)** Mean biweekly relative leaf chlorophyll content of yams in pigeonpea–yam cropping system. PA, pigeonpea in alley; PB, pigeonpea as border. Source: Owusu Danquah (2020).

TABLE 1 | The land equivalent ratio (LER) of the pigeonpea–yam cropping system at Fumesua and Ejura for 2018 and 2019 cropping seasons.

Location	Cropping system	Relative yield				LER	
		Pigeonpea		Yam			
		2018	2019	2018	2019	2018	2019
Fumesua	Yam in PA	0.30[a]	0.15[a]	1.32[a]	1.24[a]	1.62[a]	1.39[a]
	Yam in PB	0.27[b]	0.14[b]	1.14[b]	1.13[b]	1.41[b]	1.27[b]
Ejura	Yam in PA	0.38[a]	0.17[a]	1.31[a]	1.29[a]	1.69[a]	1.46[a]
	Yam in PB	0.33[b]	0.14[b]	1.11[b]	1.21[b]	1.44[b]	1.35[b]
SED (5%)		0.024		0.059		0.059	
Mean		0.24		1.22		1.46	
Location (Loc)		0.1938		0.5319		0.176	
Year (Yr)		<.0001		0.8691		0.0023	
Cropping system (CS)		<.0001		<.0001		<.0001	
Loc*Yr		0.0028		0.1637		0.4981	
Loc*Cs		0.0004		0.6407		0.4928	
Yr*Cs		0.1625		0.0030		0.0038	
Loc*Cs*Yr		0.4837		0.3432		0.4759	

LER, land equivalent ratio; PA, pigeonpea in alley; PB, pigeonpea as border. Means with the same alphabets within a location indicate no significant ($P \leq 0.05$) differences among treatments. Source: Owusu Danquah (2020).

nutrient and water use efficiency to the benefit of the associated food crop (Ribeiro-Barros et al., 2018; Kuyah et al., 2019; Akoto et al., 2020). Tsufac et al. (2021), evaluated the role of agroforestry as a sustainable agricultural practice option for soil fertility management in Cameroon. The study revealed a significant improvement in soil with agroforestry practice which was also perceived by most farmers. The productivity of maize significantly improved when integrated with pigeonpea (Musokwa et al., 2019). The productivity and profitability of cowpea, maize, and cassava significantly improved over their monocrop counterpart upon integration with bamboo (Akoto et al., 2020). The integration of Agroforestry trees such as *Gliricidia sepium and Leucaena leucocephala* into yam cropping system improved yam productivity (Maliki et al., 2017). **Table 1** shows the land Equivalent Ratio (LER) and improvement in pigeonpea–yam intercrop compared to their monocrops. More than one (1) LER indicates the significant improvement of yam productivity resulting from the integration of pigeonpea. When yam was planted in alleys of pigeonpea (PA) with pigeonpea as live-stakes, the productivity was better than when yam was planted with the borders of pigeonpea (PB) and pigeonpea stakes cut and used as stakes. Intercropping efficiency of 39–69 and 27–44% were observed for planning yam in alleys of pigeonpea and planning yam with pigeonpea as border respectively. Thus 27–69% land area of the monocrop yam would be needed to achieve a similar yield as the pigeonpea–yam intercrop. This has implications on forest conservation and land use management especially for yam which is associated with deforestation and land degradation (Ennin et al., 2014; Owusu Danquah et al., 2015). According to the report of (Ministry of Food Agriculture (MoFA), 2018), yam production in Ghana increased by 2.39% while the area under yam cultivation within the same period also increased by 2.21 suggesting about 1:1 direct relation between area under cultivation and production. This means yam production in Ghana increases as areas under production increase. This has bad implications for land resource conservation and climate change.

The resource use efficiency and productivity increase associated with the integration of trees and shrubs has demonstrated agroforestry's ability to improved and sustained productivity whiles conserving the resources on which production depends (the land). Promotion and adoption of the pigeonpea–yam cropping system as an improved technology option for yam production in Ghana would at least conserved about 27% of the land currently under yam production without affecting production. This is also welcoming since to be able to mitigate climate change, forest and tree conservation would be needed as carbon sinks.

Integration of Trees and Shrubs on Farmlands Facilitates SOC Storage

The increasing greenhouse gases (GHG) (Carbon dioxide, nitrous oxide, methane) in the atmosphere continues to be a challenge and result of global climate change. The warmest earth's surface temperature has been recorded since 2016 resulting in extreme weather conditions and its adverse effect on crop production (Gupta et al., 2017; Jones, 2017). There is, therefore, the need to pursue climate-smart technologies that increase carbon storage especially for smallholder farmers who have been predicted to be worse affected by climate change due to their limited adaptive capacity (Manaye et al., 2021). Agroforestry has been observed to be one of the low costs and sustainable technologies for mitigating climate change. This is because of its ability to provide many ecosystem services which improve agroecosystem biodiversity and productivity (Goncalves et al., 2021). Global agricultural land is about 10% with a carbon stock of about 3–18 t C ha^{-1} (Zomer et al., 2009). Agroforestry could sequester about 0.29–15.21 and 30–300 Mg C ha^{-1} $year^{-1}$ carbon in the biomass above and below ground (soil) respectively (Nair et al., 2009; Nath et al., 2021). Brown et al. (2012) observed that agroforestry systems in East and West Africa alone has the potential to store about 6–22 Mg CO_2 ha^{-1} $year^{-1}$. Manaye et al. (2021) evaluated tree diversity and carbon stocks in agroforestry systems in Ethiopia and observed a high tree species diversity and potential above and below ground carbon stock of about 77–135 Mg ha^{-1} on smallholder farmers' fields. The study suggested, agroforestry to be a very important means of storing carbon. **Figure 9** shows SOC loss from the Forest, transition, savannah, and coastal soils of Ghana when subjected to pigeonpea residue incorporation in the soil, pigeonpea rotation with yam, and use of sole inorganic fertilizer. Long-term (10 years) stimulation of soil organic matter showed a decline in SOC on all treatments. However, the decline was least when pigeonpea biomass was incorporated (−0.3 Mg ha^{-1} $year^{-1}$) followed by when sole fertilizer (−0.43 Mg ha^{-1} $year^{-1}$) and pigeonpea rotation with yam (−0.42 Mg ha^{-1} $year^{-1}$) with the control of sole inorganic fertilizer recording the worse decline in SOC of −0.51 Mg ha^{-1} $year^{-1}$ (Liu et al., 2021).

Under the clean development mechanism (CDM), the approach of afforestation and conservation of forest to serve as carbon sinks is seen as a hindrance to the agenda of increasing food production to feed the increasing population (Apuri et al., 2018; Waldén et al., 2020). Integration of trees and shrubs on farmlands addresses this issue, food production can be sustained whiles maintaining the trees and shrubs to serve as carbon sinks on the same piece of land.

Integrated Soil Fertility Management (ISFM) in the Face of Climate Change

The productivity of crop depends very much on the fertility of the soil. Therefore, improving soil fertility is key to improving smallholder farmers' productivity, income, and livelihood. Soil fertility is on a decline in sub-Saharan African (Nalivata et al., 2017; Stewart et al., 2020). There is a yield gap of about 4.9, 4.5 t ha^{-1} between potential and actual yields of maize and rice respectively (Rong et al., 2021). According to the [Global Yield Gap and Water Productivity Atlas (GYGA), 2021] (GYGA-www.yieldgap.org), maize a very important food security crop, yield under rainfed conditions is just about 10–30% of the potential yield. Soil nutrition and precipitation have been observed to be the major limiting factors affecting cereals and other crop yields in sub-Saharan Africa (AGRA, 2016; Hadebe et al., 2017; Kihara et al., 2017; Saito et al., 2019; Epule et al., 2021). Fertilizer usage was promoted to address the situation, but the inability of smallholder farmers to afford mineral fertilizers hampers fertilizer usage (Komarek et al., 2017; Patrick et al., 2018). Also, the ability to transport to their fields because of the poor road network and technical know-how in the application

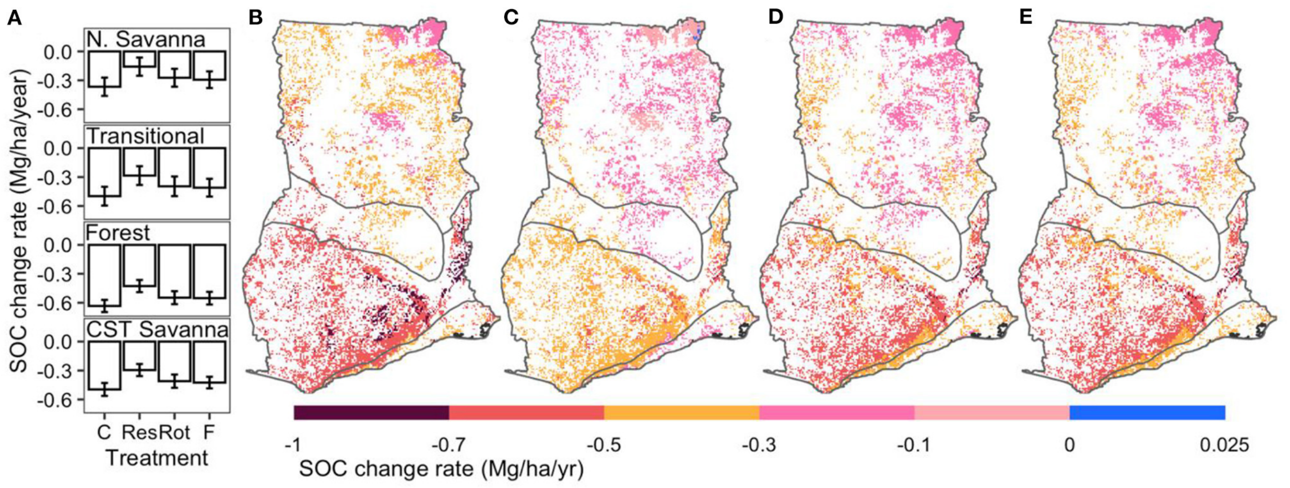

FIGURE 9 | Response of soil organic carbon (SOC) change rate to management treatments across Ghana. **(A)** Average SOC change rate by agroecological zone under the four treatments, and **(B–E)** SOC change rate under the four respective treatments: control, pigeonpea residue incorporation, pigeonpea–yam rotation, and yam with fertilizer addition. N. Savanna, northern savanna; CST savanna, coastal savanna; C, control; Res, residue; Rot, rotation, and F, fertilized. Source: Liu et al. (2021).

and usage of fertilizers are other reasons (Mugwe et al., 2019; Langyintuo, 2020).

The use of fertilizer alone does not promote long-term soil organic carbon buildup, soil fertility, and crop productivity (Raimi et al., 2017; Singh, 2018; Singh et al., 2019). Although, organic fertilizer especially plant biomass has been noted to promote soil health by building soil organic matter, getting sufficient quantities for sustainable soil fertility and food production is a challenge (Place et al., 2003; Biramo, 2018). Therefore, Integrated Soil Fertility Management (ISFM) approach which combines organic and inorganic fertilizers are being promoted as a viable option for sub-Saharan Africa. Integrated Soil Fertility Management (ISFM) is a soil fertility management practice where organic, inorganic (fertilizer), and improved germplasm are combined and adapted to the local conditions resulting in improved nutrient use efficiency and crop productivity (Vanlauwe et al., 2010; Mugwe et al., 2019; Gram et al., 2020). The combined use of organic and Inorganic fertilizers in ISFM resulted in improved productivity of most crops such as maize (Mahmood et al., 2017), Rice (Moe et al., 2017), Tomatoes (Islam et al., 2017), and Yam (Owusu Danquah et al., 2017, 2020). The use of ISFM reduces the inorganic fertilizer requirement whiles improving crop productivity. **Figures 10A,B** indicates a third and half recommended fertilizer rate of 45–45–60 N–P_2O_5-K_2O kg ha^{-1} (Ennin et al., 2016) with integration of pigeonpea biomass would be enough for sustainable yam production on continuously cropped fields.

Preceding yam with pigeonpea resulted in a reduction of the inorganic and organic fertilizers required for sustainable yam production to a third (15–15–15 N–P_2O_5-K_2O kg ha^{-1}) and a half (3 t ha^{-1}) respectively (**Figure 10A**). Also, the integration of pigeonpea into the yam cropping system resulted in the reduction of the inorganic fertilizer required for sustainable yam production to half (23–23–30 N–P_2O_5-K_2O kg ha^{-1}) (**Figure 10B**). Thus, the integration of agroforestry trees into cropping systems holds a key in making readily available nutrient reach biomass and reducing the quantities and cost of inorganic fertilizers for sustainable soil fertility management and food security in sub-Saharan Africa.

CONCLUSION AND WAY FORWARD

This paper provides one of the few assessments of the impact of carbon smart technologies on soil, crop and environment and the attendant effect on household livelihood outcomes—food security. Yield gaps are greater in many developing countries, there is considerable need for better assessment of carbon smart technologies to establish viable options for higher productivity. The review showed that conservation agriculture and agroforestry offer the option to increase carbon storage to mitigate the effect of climate change whiles improving and sustaining food production to ensure food security. To be able to improve farmers resilience to climate change and improve food production calls for the adoption of these climate smart technologies by farmers in crop production. Farmer participatory demonstrations of the benefits of these climate smart technologies would make it attractive. Although the adoption of these climate smart technologies would result in improved and sustainable productivity in the long-term, most of these technologies in the short-term require trade-offs in productivity. Well structure incentive schemes should be made available to support farmers to encourage adoption. The use of carbon smart technologies is increasingly gaining recognition under the Kyoto protocol for mitigating climate change. Upon adoption of climate smart farming practices by smallholders, resilience to climate change would improve, resulting in strides

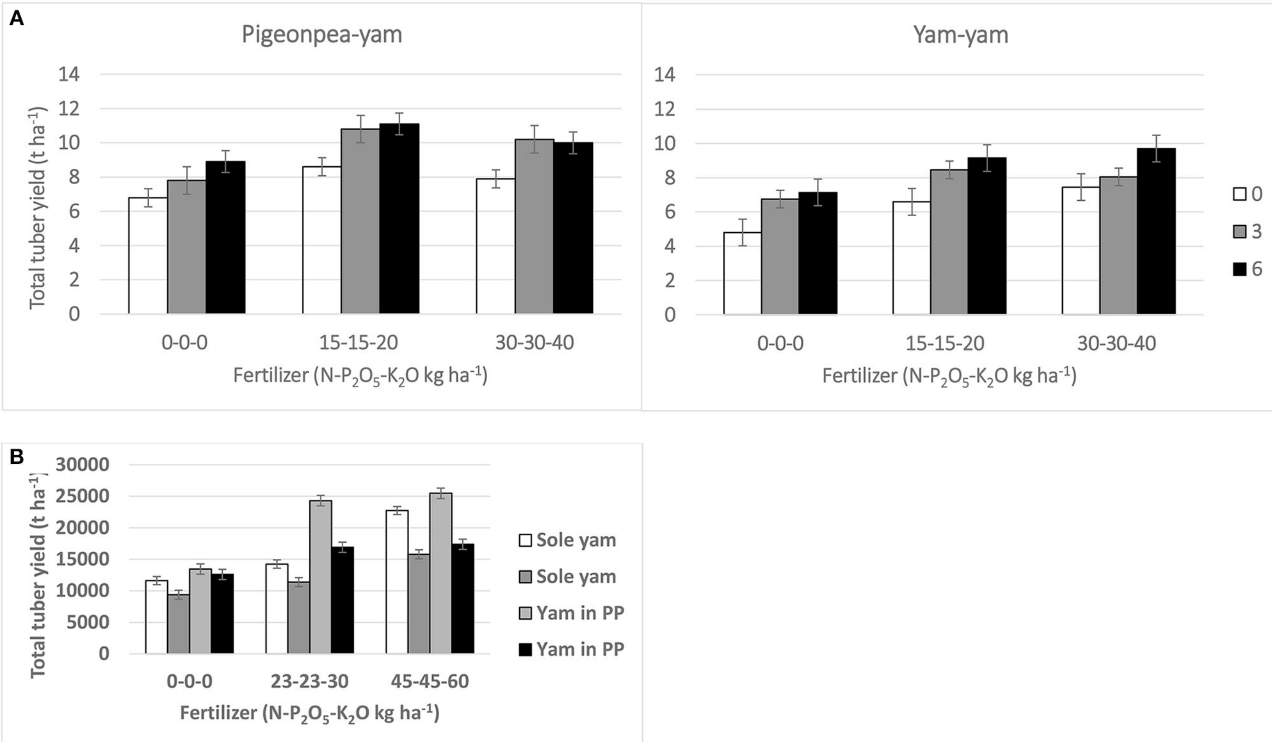

FIGURE 10 | (A) Integrated Soil Fertility Management (ISFM) reduced the inorganic and organic fertilizer (poultry manure) requirement to a third and half respectively for yam production (0–0–0, 15–15–20, 30–30–40 N–P_2O_5-K_2O kg ha^{-1}) Source: Owusu Danquah et al. (2017). **(B)** Integrated Soil Fertility Management (ISFM) reduced the organic fertilizer requirement to half and improved the tuber yield. PP, pigeonpea biomass. Source: Owusu Danquah (2020).

towards addressing the SDG's of No poverty (1), No hunger (2), Good health and well-being (3), Climate action (13) and Life on land (15) among others.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding authors.

AUTHOR CONTRIBUTIONS

SY: conceptualization, methodology, investigation, and writing—original draft. EOD: conceptualization, methodology, and writing—review and editing. PO-D: conceptualization, methodology, and writing—review and editing. KA and ENT: investigation and writing—review and editing. All authors contributed to the article and approved the submitted version.

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frontiers in Sustainable Food Systems

ORIGINAL RESEARCH
published: 05 October 2021
doi: 10.3389/fsufs.2021.739061

Farmers' Knowledge Is the Basis for Local Level Agro-Forestry Management: The Case of Lemo Woreda in Hadiya Zone, Ethiopia

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OPEN ACCESS

Edited by:
Emmanuel Donkor, Humboldt University of Berlin, Germany

Reviewed by:
Faizal Adams, Kwame Nkrumah University of Science and Technology, Ghana
Yong Sebastian Nyam, University of the Free State, South Africa

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Specialty section:
This article was submitted to Climate-Smart Food Systems, a section of the journal Frontiers in Sustainable Food Systems

Received: *09 July 2021*
Accepted: *03 September 2021*
Published: *05 October 2021*

Citation:
Horamo Y, Chitakira M and Yessoufou K (2021) Farmers' Knowledge Is the Basis for Local Level Agro-Forestry Management: The Case of Lemo Woreda in Hadiya Zone, Ethiopia. Front. Sustain. Food Syst. 5:739061. doi: 10.3389/fsufs.2021.739061

This research was designed to investigate the hypothesis that farmers practising traditional agro-forestry which dates back for centuries have accumulated immense knowledge of agro-forestry, which can be captured and incorporated into formal development programmes to improve it. Farmers' knowledge must be documented, valued and integrated in order to maximise its importance for planning and decision-making. This research aimed to investigate and document farmers' knowledge of managing agro-forestry and the contribution to sustainable management of natural resources. Accordingly, questionnaire surveys were conducted in six villages from three peasant associations. In total, 73 households were selected for interview and the data collected were analysed using SPSS (Statistical Package for Social Science) version 26. The findings revealed tree species that contribute to crop yield improvement and the important role agro-forestry trees play with regard to soil fertility. Farmers' strategies to associate trees and shrubs in their farmlands were revealed. Tree species with a negative effect on crop yields were identified and recorded. Farmers reported and ranked in the order of importance, opportunities and constraints in the management of agro-forestry. Farmers' accumulated knowledge of tree–crop and tree–animal interactions, the role of trees in soil fertility, crop and livestock improvement, revealed in the study can significantly enhance the stainability of agriculture. If local knowledge is not documented, it remains largely inaccessible to development workers seeking solutions to locally defined problems.

Keywords: agro-forestry, farmers' knowledge, tree-animal interaction, tree-crop interaction, crop yield

INTRODUCTION

Local farmers are the inhabitants of a particular geographic rural area; they live by rearing crops and animals. They have developed over centuries a culture and belief system which is distinct from the so-called modern international system of knowledge (Njiraine et al., 2010). Through this cuture and belief system, local farmers have accumulated tremendous indigenous knowledge about their surrounding natural resources, which has enabled them to survive often harsh environmental conditions (Payyappallimana and Koike, 2010). Knowledge is regarded as the body of mental inferences and conclusions that people build from different elements of information and which allows them to take informed actions in a given context (Leeuwis, 2013). It is an output of learning, reasoning and perceptions, and it forms the basis for predictions of future events (Cheveau et al., 2008). Knowledge, especially traditional knowledge is not static but dynamic since it has to evolve over time in response to new challenges.

The new challenges humanity is now facing is environmental degradation due mainly to exponential human population growth that put unprecendented pressure on natural capital. Other modern-day challenges include over-exploitation of natural resources, climate change, alien invasive species, deforestation and pollution (De Groot et al., 2010; Sjögren, 2015). The negative impacts of these environmental challenges are particularly felt by local population in rural areas because of natural predispositions driven by poverty, poor education and collapsing medicinal system, and more critically food insecurity. In response to food insecurity, modern input to farming such as mineral fertilisers have been introduced to traditional farming (Larson et al., 2016). However, the use of mineral fertilisers is declining as they are increasingly beyond the means of most small-scale farmers (Chowdhury et al., 2009). For example, Meijer et al. (2015) reported that one of the major constraints to crop production faced by smallholder subsistence farmers is the inadequate supply of nutrients. Even fertilisers, if used excessively and aggressively, may pose additional environmental and health problems, e.g., water pollution.

In this context, some suggested that the investigation of traditional knowledge related to farming, e.g., agro-forestry, in search of a way to improve traditional farming practises is the way forward in rural African context (Brown et al., 2018). Previous research tended to focus on determining the appropriate type of agro-forestry needed to obtain the best yields for particular soil types and specific agro-ecological locations. This approach emphasised the use of external inputs and expensive technologies (Larson et al., 2016) and often disregarded traditional farmers' knowledge and the resources at their disposal. For example, several development projects and policies have collapsed because of a failure to understand and integrate local knowledge, and how this influences the way farmers manage natural resources (Musinguzi et al., 2015). This prompts the call for research to gradually shift towards an approach based on integrated traditional agro-forestry practises into improvement strategy of crop production. This approach requires a thorough scientific understanding of the underlying biological processes of integrated agro-forestry management and aims to promote options that make the best use of locally available knowledge and inputs (Dawoe et al., 2012).

Sustaining soil fertility through agro-forestry has become a major issue for agricultural research and development in sub-Saharan Africa (Dagar et al., 2013; Sjögren, 2015).

Agro-forestry, as a scientific discipline is relatively recent, although cultivating trees and agricultural crops in intimate combination with one another on the same farm is an ancient practise used by farmers throughout the world (Kindeya, 2004; De Groot et al., 2010; Dagar et al., 2013; Sjögren, 2015). During the past few decades, interest in agro-forestry has increased substantially. Agroforestry presents numerous benefits that need to be preserved and increased. For example, agroforestry sysetms control runoff and soil erosion, thus preventing the loss of water and soil and nutrients that crops needs for productivity.

They can maintain soil organic matter and biological activity at levels satisfactory for soil fertility. This depends on an adequate proportion of trees in the system—normally at least 20% crown cover of trees to maintain organic matter over systems as a whole. They can maintain more favourable soil physical properties than agriculture, through organic matter maintenance and the effects of tree roots. They can lead to more closed nutrient cycling than agriculture and hence to more efficient use of nutrients. This is true to an impressive degree for forest garden/farming systems. They can cheque the development of soil toxicities, or reduce exiting toxicities-both soil acidification and salinization can be checked and trees can be employed in the reclamation of polluted soils. They utilise solar energy more efficiently than monocultural systems different height plants, leaf shapes and alignments all contribute. They can lead to reduced insect pests and associated diseases. They can be employed to reclaim eroded and degraded land. Agro forestry can augment soil water availability to land use systems. In dry regions, though, competition between trees and crops is a major problem. Nitrogen-fixing trees and shrubs can substantially increase nitrogen inputs to agro forestry systems. Trees can probably increase nutrient inputs to agro forestry systems by retrieval from lower soil horizons and weathering rock. The decomposition of tree and pruning can substantially contribute to maintenance of soil fertility. The addition of high-quality tree prunings leads to large increase in crop yields. The release of nutrients from the decomposition of tree residues can be synchronised with the requirements for nutrient uptake of associated crops. While different trees and crops will all have different requirement, and there will always be some imbalance, the addition of high quality prunings to the soil at the time of crop planting usually leads to a good degree of synchrony between nutrient release and demand. In the maintenance of soil fertility under agro forestry, the role of roots is at least as important as that of above-ground biomass. Agro forestry can provide a more diverse farm economy and stimulate the whole rural economy, leading to more stable farms and communities. Economics risks are reduced when systems produce multiple products.

Unfortunately, agro-forestry activities are now declining in many parts of Sub-Saharan Africa (SSA) (Alemayehu et al., 2009) due to challenges leading farmers to either abandon entirely the traditional agro-forestry using natural fallow to restore soil fertility or to leave land fallow for long enough for it to be effective (Chitakira and Torquebiau, 2010).

The present study sought to understand how the farmers in the Woreda have managed the complex nature of the interactions between agricultural production and tree cultivation in order to appreciate the role of farmers knowledge. The study was designed with the intention to study and document farmers' knowledge of managing agro-forestry and bridge their overall contribution to the future development of agro-forestry and sustainable agriculture. The research questions considered include: (1) What is the role of the farmers' knowledge in the management of sustainable agriculture and agro-forestry? (2) What are the

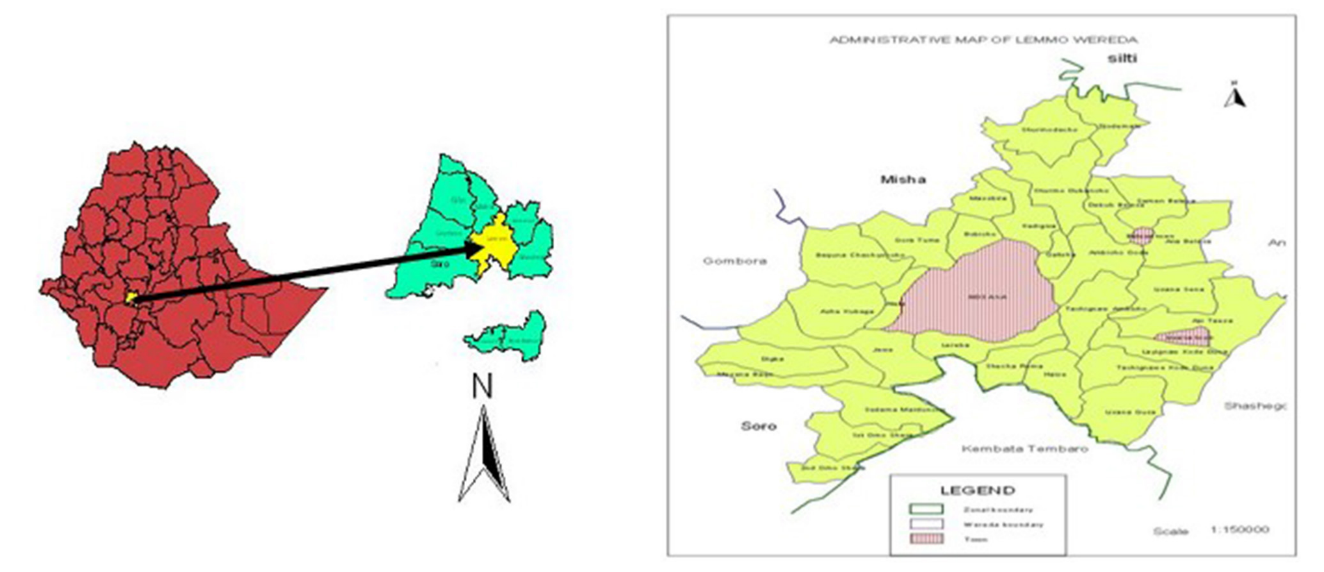

FIGURE 1 | Location of Hadiya zone and study area Lemo Woreda in Ethiopia.

opportunities and challenges for managing the existing agro-forestry in the study area?

METHODS AND MATERIALS

Description of the Study Area

The study area (Lemo Woreda) is situated in Hadiya Zone in Southern Nations Nationalities and Peoples Regional State (SNNPRS) (**Figure 1**). The study area geographically lies between Latitude 07^0 $41'$N and Longitude 037^0 $31'$E. Topography of the study area is rugged high land and hilly areas with a slope range of 2 to 30%. Generally, the terrain is mountainous, undulating and very much prone to soil erosion. Hosanna city in Lemo Woreda is the capital of the Hadiya zone. It is situated 230 km south of Addis Ababa, the capital of Ethiopia.

The soils in the study area are intensively cultivated and greatly degraded through erosion. Measures are being taken by the agriculture extension officers, individual farmers, interested groups and NGO's (Non-Governmental Organisations) to address the soil erosion challenge and loss of soil fertility. This is done through creating awareness and training of farmers on how to control soil loss by constructing physical structures supported by means to maintain soil fertility.

The Woreda is found in "*Woina Dega*" agro-climatic zone with altitudinal range of 1950–2400 m.a.s.l. It has a cool temperature range of 15–18^0C and an average rainfall of 1150 mm. The rivers and seasonal streams in the Woreda supply water for both drinking and sanitation purposes, and one of the rivers, Bilate river, is used for small scale irrigation. The major perennial rivers that flow permanently throughout the year are, Bilate and Guder which are flow into Lake Abaya on the rift valley.

In the Woreda, all of the natural vegetation and grazing lands have almost been converted into cultivated land. What remains in the area are the retained trees that are scattered in all land-use types. Farmers are already accustomed to planting some tree species to replace the former natural vegetation, to meet the demands for wood, construction and fuel. The socio economic factors may be the main reasons for diminishing forest resources (LWOAaRD (Lemo Woreda Office of Agriculture Rural Development)., 2012). Whereas, in the study areas farmers have been developing agricultural systems, domesticating animals, breeding new crop varieties and constructing irrigation systems throughout the centuries without the aid of formalised scientific approaches and agricultural extension systems (Pirker et al., 2012). The dominant land-use types in the Woreda are sedentary mixed farming with the cultivated land accounting for 89% of the total land area (LWOAaRD (Lemo Woreda Office of Agriculture Rural Development)., 2012). This indicates that there is great pressure on land. The area practises mixed farming, with complete integration of trees, crop production and animal husbandry. Animals provide food, draught power, manure for crops, and fuel. Crop residues are used as feed for animals.

Data Collection

Three Peasant Associations (PAs) were identified by purposive sampling with the assistance of local extension officers in the Woreda for the study. The selection was based on the existence of traditional agro-forestry and on accessibility of the PA. Three villages from each peasant association were selected for this study. The same number of participants was chosen from each PA. The sample size for this study was computed using kurtosis formula *i.e.,* $n = z^2qpN/e^2$ (N-1) + z^2pq Where: $p =$ Allowable error and confidence interval of (z) 95%, $N =$ total number of households or population, $n =$ sample size from total households and $z =$ confidence interval of 95% from z-table. From each PA, 73 households were selected for questionnaire interviews.

One could assume that farmers' knowledge in managing agro-forestry depends on the socioeconomic status of the farmers. The list of households was written down on a paper. Individual households were selected for study from each PA by means of simple random sampling, based on the list of households. Data collection was achieved by means of 6 enumerators i.e., 2 per PA who were trained before being assigned to collect data. The enumerators had to have a minimum of a diploma in natural resources management or related fields.

Data collection was conducted over a period of two months using pre-tested and semi-structured questionnaires. Questionnaires were designed to gather farmers' knowledge on managing agro-forestry and the implication for each household. The questionnaire was pre-tested to ensure it was able to collect the data it was intended to collect and to make adjustments as appropriate. The researchers also made observation in the area during interviews to supplement data obtained from the questionnaire interviews.

Data Analysis

Data collected were coded and then analysed using the Statistical Package for Social Sciences (SPSS) version 26. The data were summarised and descriptive statistical analysis (including frequencies, percentages, and ranks) was conducted and results interpreted accordingly.

RESULTS AND DISCUSSION

Agro-Ecological and Socio-Economic Conditions of the Study Area

The ecological or biophysical and socio-economic conditions of the study area were surveyed and are summarised in **Tables 1**, **2**. The study locations were characterised by the farmers themselves with the the research team playing a facilitation role. **Tables 1**, **2** show biophysical characteristics and land use types relating to tree, crop and animal production. The results compare fairly well with the findings of Glover et al. (2013). The land use land cover types reveal that cultivated land alone accounts for 78.5% of the total land. This implies that the study area should have to focus on tree planting on the farms to increase tree cover, as noted by Arnold and Dewees (2014). Tree planting on farmland could mean a loss of agricultural income on the short-term but has a considerable economic gain in the long run (Rahman et al., 2016).

Farmers' Knowledge in Managing Agro-Forestry

Tree–Crop Interactions

The study revealed local farmers' knowledge about tree and shrub species that contribute positively to crop yield and/or animal yield and those that potentially result in decrease of crop yield/animal yield. These findings are in agreement with findings by Glover et al. (2013) that trees and shrubs are the characteristic features in traditional agro-forestry and that trees interact through complementary, supplementary and competitive forms when they grow in proximity to crops and/or to each other. An understanding of the nature of interactions between trees and crops is of major importance in determining tree-management strategies of agro-forestry because the success of agro-forestry depends on the management of such component interactions (Schroth, 1995; Dagar et al., 2013; Yakob et al., 2014).

Positive Attributes of Trees

There was a wide awareness among farmers that without manure and/or crop residue additions soil fertility is very much reduced, particularly in the absence of improved tree fallowing and continuous farming. The threat of food insecurity was revealed as a challenge in the area because of the declining trends of soil fertility and forest destruction. All respondents agreed that a decrease in crop–yield is the indicator of a decrease in soil–fertility status. Generally, the local farmers perceived brown soils and as fertile soil and grey coloured soil as poor in fertility and not good for crop production. The farmers perceived that fertile soils were found on flat land where silt deposition takes place with gradient change from the rugged upland to the lowlying areas.

The respondents expressed knowledge of which tree species contribute to improvement of soil fertility status. Knowledge of which part of the tree/shrubs decompose faster and change to soil was revealed. Leaves were mentioned as fast–decomposing tree part followed by roots. This study confirmed that farmers have manipulated and helped the slow evolution of agro-forestry to fit the environment and their needsThe respondents were quick to tell which tree species have a potential for improving crop yield, which ones decompose fast and supply large amount of litter. For instance, the farmers reported crops under managed *Acacia abyssinica* as having a good potential to improve cropyield. The findings were consistent with the observations by Ponge (2013) that crop yield is better around tree stumps than elsewhere in fields. Similarly, Bishaw et al. (2013) reported that farmers experience yield improvements when crops were planted with multipurpose trees. A study by Goldammer (2013) revealed a yield increment of sorghum and maize associated with *Acacia albida*. This study confirms the findings in a study by Cerdán et al. (2012) that farmers had a good understanding of how and when leaf material is decomposed and release nutrients into the soil substrate.

Respondents in this study indicated that the order of importance with regard to soil fertility as: *Erthrina abyssinica*> *Vernonia auriculifera*> *Cordia africana*> *Adathoda schemperiana*> *Croton macrostachys*> *Ficus sur*> *Vernonia amygdalina.* There exists considerable knowledge of agro-forestry including selection of species for incorporation into farmlands. Trees incorporated or retained for tree-crop combinationshave positive attributes as regards yield improvement (**Table 3**). It was found that some individuals were not interested in incorporating *Acacia species* into their farms, mainly because of the thorny nature of the species, which causes difficulties during agricultural activities.

The respondents listed seven indigenous tree/shrub species that they perceived to improve crop yield (**Table 3**). Crops grown under these trees are believed to grow vigorously. These tree species are characterised by light crown and small crown dimension which minimise light competition with companion

TABLE 1 | Biophysical information.

Attributes	Lemo woreda	Peasant associations		
		Masbira	Shecha	Lissana-senna
Altitude (m.a.s.l)	1950–2400	2140–2360	1950–2200	2100–2240
Rainfall (mm a^{-1})	900–1400	900–1400	900–1400	900–1400
Temperature (^{0}C)	15–18^{0}C	15–18^{0}C	15–18^{0}C	15–18^{0}C
Topography (slope %)	5–54%	4–15%	2–15%	2–16%
Location		07^0 35'N	7^0 29'N	07^0 33'N
		037^0 55'E	037^0 52'E	037^0 55'E
Average distance from Hossana (Km)	-	11	9	12

Source: Survey results.

TABLE 2 | Land use types.

Land Use	Lemo woreda		Peasant associations					
			Masbira		Shacha		Lissana-senna	
	Area (ha)	Percent	Area (ha)	Percent	Area (ha)	Percent	Area (ha)	Percent
Cultivated land	27,441	78.5	545	78.4	512	64	907	63.3
• Annual crops	23,697	67.8	497	71.4	392	49	698	48.7
• Perennial Crops	3,744	10.7	48	7	120	15	209	14.6
Wood lot, bush& shrub land	2,418	7	50	7.1	-	-	16	1.1
Area closure	349	1	5	0.7	61	7.6	275	19.2
Grazing land	1,079	3	92	13.2	48	6	35	2.4
Others	3,686	10.5	4	0.6	179	22.4	201	14
Total	34,973	100	696	100	800	100	1,434	100

Source: Survey results.

crops. The tree species identified as having positive attributes for crop yield improvement include *Grevillea robusta, Acacia abyssinica, Millettia ferruginea, Acacia saligna, Ekbergia capensis and Ricinus communis*.

This research revealed a considerable wealth of local knowledge about quality of leaf litter. Considerable knowledge was found on litter decomposition and characterisation in terms of early-decomposing and late- or slow-decomposing litter. It was mentioned that rates of of decomposition of litter from different trees and shrubs were variable. Crop yield improvement resulting from tree or shrub litter decomposition was well-appreciated by respondents. There was a general understanding among the locals regarding the correlation between crop yield improvement and litter decomposition. Farmers also appreciated the significant role that soil microorganisms play in litter decomposition. During the discussions the most frequently mentioned tree and shrub species with early-decomposing litter are in the following order: *E. abyssinica> V. auriculifera> C. africana> A. schemperiana> C. macrostachyus> F. sur> V. amygdalina* (**Table 3**). **Table 4** illustrates the criteria used by the local farmers to characterise the trees on their farmland.

Farmers in this study confirmed having recognised the soil-fertility status of their farmland declining. The respondents indicated that the soil had become poorer in terms of fertility and hardly supports crop growth beside weeds. The farmers in the area could identify fertile soils by looking at the colour: fertile soil is "*bunama*" in colour or "wet sand" while poor soil is "white or ash." This finding is consistent with a study conducted in Zimbabwe by Chuma et al. (2000) which showed that farmers can explain soil fertility decline to an extent of predicting that no yield could be obtained in certain soils without applying fertilisers. A study by Nandwa et al. (2000) reported that the farmers considered decline in soil fertility as the main constraint to crop production and productivity. Thus, several studies have confirmed the capability of farmers to assess the suitability of soils for crop production. Farmers have developed various techniques to improve or maintain soil fertility (Munyua and Stilwell, 2013). A study by Elias (2000) showed that there was a wide use of leaf litter by resource-poor farmers to manage soil fertility, owing to the prevalence of bushes near farms. A study by Munyua and Stilwell (2013) showed that *Faidherbia albida* sheds its leaves, the roots draw nutrients and the tree fixes nitrogen to enrich the soil and improve crop yields and also reported the value of *C. africana* trees to soil enrichment.

Adverse Effects of Woody Plants on Crops

Interviews in this study revealed the negative impacts that trees and shrubs have on crops. Species mentioned as having notable negative effects on crop yields are *Eucalyptus globules and Eucalyptus camaldulensis*. These species are not allowed

TABLE 3 | Tree species for soil fertility.

S/N	Tree species	1	2	3	4	5	6	7	Point	Rank
1	*Erthrina abyssinica* (Er)		Er	Er	Er	Er	Er	Er	6	1
2	*Ficus sur* (Fi)			Co	Co	Ve1	Fi	As	1	6
3	*Cordia africana* (Co)				Co	Ve1	Co	As	4	3
4	*Croton macrstachyus* (Cr)					Ve1	Cr	Cr	2	5
5	*Vernonia auriculifera* (Ve1)						Ve1	Ve1	5	2
6	*Vernonia amygdalina* (Ve2)							As	0	7
7	*Adathoda schemperiana* (As)								3	4

Source: Survey results.

TABLE 4 | Farmers strategies to characterise trees and shrubs in their farmlands.

S/N	Criteria	% of respondents ($n = 73$)	*Rank*
1	Palatability	62(83.5%)	3
2	Soil fertility/ Decomposability	69(94.5%)	1
3	Branch volume	42(57.5%)	5
4	Construction wood	63(86.3%)	2
5	Shade	55(75.3%)	4
6	Unpalatable	20(27.4%)	7
7	Densely grown	30(41%)	6

Source: Survey results.

to grow in crop fields due to their perceived negative effects. The adverse effects were explained in terms of competition, killing of other vegetation and late or slow decomposition. Some participants expressed that the land on which *Eucalyptus* roots existed was no longer good agricultural land as it becomes dry. The roots of *E. globules and E. camaldulensis* were perceived to have a negative effect to crops, owing to severe competition for nutrients and water. The allelochemical (acidic) from *E. globulus* tends to kill the vegetation beneath the canopies and around the *E. globulus*. With regard to late decomposition *Eucalyptus* was clearly distinguished. The leaves and branches of *E. globulus* and *E. camaldulensis* were reported to remain on the ground undecomposedfor several months or years. *E. globulus* was ranked by the respondents as the top-most in having an adverse influence on crops. Despite knowledge of the negative effect of *Eucalyptus* on crops, the farmers still planted *Eucalyptus* close to their farmlands.

In this study *E. globules* and *E. camaldulensis were* commonly identified to have a negative influence on crop yield. It was clearly noted that *Eucalyptus* species dry up the land and compete with crops for nutrients and water. The respondents' opinions in this study confirm studies conducted in Ethiopia by Kidanu et al. (2005) and Nyssen et al. (2009) which showed that competition for water, soil nutrients and allelopathic effects between *Eucalyptus* and annual crops may occur close to the tree rows and that tree species such as *Eucalyptus spp*., *Cupressus lusitanica*, *Olea europaea*, *Podocarpus falcatus, Juniperus excelsa* have such effects. In a study by Tafere and Nigussie (2018) in Sidama, both the farmers and extension workers confirmed that the planting of *Eucalyptus* affected adjacent crops while Tafere and Nigussie (2018) established that *Eucalyptus* takes up a high amount of water and nutrients from the soil so that it might affect crops planted next to it. A study in Southern Ethiopia by Tesfaye (2005) also revealed that *E. camaldulensis* was perceived as having competitive effects and and the farmers would not allow it to grow together with crops. Thus the findings in the present study are in line with findings from related studies.

Tree–Animal Interactions

Livestock play an important role in the livelihoods of the community of the study area. Farmers are highly concerned about the availability of fodder. As such, local farmers utilise woody plants to supplement the meagre supply of fodder for livestock (**Table 5**). This study showed that farmers' preferences for fodder and shrub species were influenced by the feeding preference of their livestock or the palatability of livestock browse. It was reported that livestock were fed from trees and shrubs mainly in the dry season when rangelands will not be having sufficient grass (**Table 5**). Woody species commonly used for fodder in the area during the dry season are *Sesbamia sesbania, Persea americana, Erythrina abyssinica, Chamcytesus palmensis, Olea eurropaea, Verninia amygdalina, Enset ventricosum, Adathoda schemperiana, and Grevillea robusta*.

Table 5 shows a list of fodder trees/shrubs. The order of browsing preference starting with the most preferred was: *E. ventricosum*> *A. Schemperiana*> *V. amygdalina*> *O. eurropaea*> *S. sesbania*> *C. palmensis*> *G. robusta*> *P. americana*> *E. abyssinica*. The leaves, new shoots, barks, fruits, pods or flowers were the tree parts used for fodder. Farmers indicated some order in preference in the use of tree or shrub parts for fodder. A general pattern or order of preferences derived from the farmers' responses was: older leaves > new shoot > bark > fruit/pods > flowers. Trees were identified as "most palatable" through to "not palatable" based on the preferences of the livestock.

It was also noted in the study area that there exists considerable knowledge on the adverse effects of trees/shrubs on animal health. For example, a leaf of *Agave sisalina* is considered very dangerous for livestock mainly due to its hard fibre which is difficult to digest and is capable of blocking the oesophagus.

TABLE 5 | Trees and Shrubs used for Fodder and preference ranking.

S/N	Tree / shrub species	Percentage of respondents (*n* = 73)	Ranking
1	*Sesbamia sesbania*	34(46%)	5
2	*Persea americana*	24(33%)	8
3	*Erythrina abyssinica*	20(27%)	9
4	*Chamcytesus palmensis*	31(43%)	6
5	*Olea europaea*	43(59%)	4
6	*Verninia amygdalina*	56(77%)	3
7	*Enset ventricosum*	71(97%)	1
8	*Adathoda schemperiana*	58(80%)	2
9	*Grevillea robusta*	28(38%)	7

Source: Survey results.

TABLE 6 | Main Constraints in agro-forestry management.

S/N	Challenges	Percentage of respondents (*n* = 73)	Rank
1	Shortage of land	69(94%)	2
2	Free grazing	70(96%)	1
3	Drought	63(86%)	3
4	Shortage of labour	50(68%)	5
5	Shortage of water	53(73%)	4
6	Shortage of seedling	45(61%)	6

Source: Survey results.

R. Communis has also been mentioned as being involved in the bloating of livestock stomachs and in causing illness. When leaves of *A. abyssinica* are fed to goats during the dry season, they may cause sickness. Other uses of local trees such as fumigation of storage of some animal products like milk using *O. europaea* were highlighted. This result confirms the existence of indegenous knowledge technologies in the communities appropriate to the needs of farmers (Agrawal, 1995). Rural people also possess knowledge regarding the various animal rearing practises i.e., which trees and shrubs are toxic to the animals and which can be used for medicine, how to cure diseases and how to maintain animals in good health. In the study area, farmers use leaves of *Allophylus abyssinica* and *Calpurnea aurea* to cure their animals, *O. europaea* and *V. amygdalina* were used by farmers to fumigate and clean milk and local beer "*tella*" pots to ensure good taste, and smell. This observation is in line with the report by Yirga (2010).

Opportunities and Challenges to Agro-Forestry

Constraints experienced in the management of agro-forestry were mainly free grazing (96%), shortage of land (94%), drought (86%), water scarcity (73%), shortage of labour (68%) and shortage of seedlings (61%) (**Table 6**). Constraints that were mentioned in the management of agro-forestry nursery activities include water shortage (73%), lack of polyethene tube (61%), seed shortage (77%), pre sowing treatment (74%), knowledge limitations (68%), pest and disease (5%) and labour shortage (56 %) (**Table 7**). These findings compare faily well with those by Chitakira and Torquebiau (2010) in a related study in Zimbabwe, although in the latter case, water and fencing to protect crops were the top-most perceived challenges. Training in the behaviour of some species as regards germination, and in the use of polyethene tubes was suggested as a way to address knowledge limitations. The responsibility of making important tree management decisions was revealed to be largely for the men although in some cases women are also involved (**Table 8**).

TABLE 7 | Constraints in Agro-forestry nurseries.

S/N	Constraints	Percentage of respondents (*n* = 73)	Rank
1	Knowledge limitations	50(68%)	5
2	Pre sowing treatment	54(74%)	4
3	Polyethene tube	61(83%)	2
4	Labour shortage	41(56%)	6
5	Shortage of water	64(88%)	1
6	Seed shortage	56(77%)	3
7	Pest and disease	4(5%)	7

Source: Survey results.

TABLE 8 | Tree management decision.

S/N	Tree/ shrub species	Men	Women	Both
1	*Acacia abyssinica*	37(50%)	15(20%)	21(30%)
2	*Cordia africana*	55(75%)	15(20%)	3(4%)
3	*Croton macrostachyus*	44(60%)	21(30%)	8(10%)
4	*Cupressus lusitanica*	51(70%)	15(20%)	8(10%)
5	*Junipers procera*	55(75%)	13(18%)	5(7%)
6	*Olea europeae*	59(81%)	6(8%)	8(11%)
7	*Rhamnus prinoides*	6(8%)	52(72%)	15(20%)
8	*Eucalyptus camaldulensis*	54(74%)	14(19%)	5(7%)
9	*Eucalyptus globulus*	53(72%)	16(22%)	4(6%)

Source: Survey results.

TABLE 9 | Opportunities for managing agro-forestry.

S/N	Opportunities	Percent of respondents (*n* = 73)	Rank
1	Market	72(98%)	1
2	Water harvesting	50(68%)	4
3	Tree planting farmers	53(73%)	3
4	Credit facility	44(60%)	5
5	Seedling supply	61(83%)	2

Source: Survey results.

Farmers often experiment with agro-forestry and innovate on their own account (Poudel, 2018). In many countries, rural people traditionally plant trees for a multiplicity of household uses (Yakob et al., 2014). Respondents in this study had the knowhow of constructing water-harvesting structures as a means of solving the problems of water shortage. The study also revealed the farmers' awareness of tree products and how to market them and the perceived good prices from tree product sales (**Table 9**). **Table 9** shows that a majority (98%) of the respondents sold their products in the local markets. The other opportunities inlcuded credit facility (60%), access to tree planting farmers (73%), construction of water-harvesting structures (68%) and seedling supply (83%). Farmers pointed out that they could get credit locally from Woreda Credit and Saving Institution (WCSI). Understanding such farmers' experiences and meeting farmers' aspirations is important in the scaling-up of agro-forestry (Girard, 2015).

CONCLUSION AND RECOMMENDATIONS

It has been shown that local farmers have accumulated a vast wealth of knowledge for managing agro-forestry over years and which has transferred from one generation to another. In the study, farmers' knowledge about tree-crop and tree-animal interraction was shown to be applicable for improvement of soil fertility, crop yield and animal health. Thus, farmers' knowledge has played a pivotal role in sustaining agro-forestry and food production systems in the study area.

This study therefore recommends the establishment of a centre where local farmers' knowledge is systematically documented and kept, probably at the local government level.

It is seen that farmers' knowledge is the basis for local level decision making for agro-forestry management in the community. So, by documenting the findings it should be possible to apply such local indegenous knowledge in harmony with the contemporary or scientific knowledge. Integrating local farmers' knowledge is important in enhancing the chances of success of development activities. If local knowledge is not documented, it remains largely inaccessible to development workers seeking solutions to locally defined problems. Further research could look into sustainable ways of integrating local farmer's knowledge with scientific knowledge in the context of climate variability and global change.

DATA AVAILABILITY STATEMENT

The datasets presented in this article are not readily available because Ethical clearance given may not permit sharing of datasets with a third party. Requests to access the datasets may be directed to 58550763@mylife.unisa.ac.za.

ETHICS STATEMENT

The studies involving human participants were reviewed and approved by College of Agriculture and Environmental Science Ethics Review Committee, University of South Africa. The participants provided their written informed consent to participate in this study.

AUTHOR CONTRIBUTIONS

YH and MC: project conception. MC: final manuscript. YH, MC, and KY: draft manuscript. MC and KY: quality control and supervision. YH: data collection and analysis. All authors contributed to the article and approved the submitted version.

FUNDING

The logistical support by the University of South Africa and Wachemo University (particularly office of research and public service) is greatly appreciated.

ACKNOWLEDGMENTS

Researchers are grateful to the farmers of Masbira, Shecha and Lissana senna PAs in Lemo Woreda who devoted their precious time to share their immense locally adapted knowledge and their experience during the critical crop planting period. Many thanks to the enumerators (Ato Adinaw Baffa, Ato Mengesha Abate, Ato Dereje Lemma, Ato Habte Asirat, Ato Chakisso Wolde and Ato Gizaw Abaka) who assisted in data collection, as well as the staff of Lemo Woreda office of agriculture and natural resources for their unreserved cooperation and support in this study.

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frontiers in Sustainable Food Systems

ORIGINAL RESEARCH
published: 26 October 2021
doi: 10.3389/fsufs.2021.762650

Climate Change Adaptation Strategies Vary With Climatic Stress: Evidence From Three Regions of Vietnam

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OPEN ACCESS

Edited by:
Enoch Owusu-Sekyere, Swedish University of Agricultural Sciences, Sweden

Reviewed by:
Yong Sebastian Nyam, University of the Free State, South Africa
Hiroshi Takagi, Tokyo Institute of Technology, Japan
Huynh Viet Khai, Can Tho University, Vietnam

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Specialty section:
This article was submitted to Climate-Smart Food Systems, a section of the journal Frontiers in Sustainable Food Systems

Received: *22 August 2021*
Accepted: *27 September 2021*
Published: *26 October 2021*

Citation:
McKinley JD, LaFrance JT and Pede VO (2021) Climate Change Adaptation Strategies Vary With Climatic Stress: Evidence From Three Regions of Vietnam. Front. Sustain. Food Syst. 5:762650. doi: 10.3389/fsufs.2021.762650

Vietnam faces several adverse climatic stresses such as increases in temperature, drought, flooding, saltwater intrusion, and sea-level rise. Past research on climate change adaptation in Vietnam has highlighted that climatic stresses and challenges faced by populations vary across the country. In this study, we are interested to know if autonomous responses also vary, depending on which stress individuals are responding to. To answer this question, we use primary-collected data of 1,306 individuals from the Mekong River Delta, Central Vietnam, and the Red River Delta. Adaptation choices of these individuals are analyzed at two levels: the household-level and the agricultural-level. We estimate multivariate probit models by Geweke-Hajivassilou-Keane (GHK) simulated maximum likelihood methods. Our results show that climate change adaptations vary depending on which stresses individuals are responding to. At the household level, droughts and floods have the strongest effect on climate change adaptation. However, adaptations at the agricultural level depend more on the impacts of the stress and less so on the climatic strss itself. Understanding what climatic stresses are already eliciting a response, and what adaptations are being used by individuals, is invaluable for designing successful climate change policies. This understanding can also help policymakers identify where gaps exist in individual climate change adaptations and fill these gaps with a public response.

Keywords: adaptation, climate change, maximum likelihood method, multivariate probit, rice, Vietnam, climatic stress

INTRODUCTION

The overwhelming consensus of experts is that the climate is changing, and humans are responsible (Oreskes, 2004; Doran and Zimmerman, 2009). Climate change refers to changes in the mean or variability of climate that persists over an extended period, typically of at least a decade, such as global warming (IPCC, 2018). Increased global temperatures bring unprecedented risks to vulnerable populations as a result of disrupting natural systems—examples are increases in the frequency and severity of droughts, floods and other extreme weather events; increased global sea-level rise; and biodiversity loss (IPCC, 2012, 2014; Mysiak et al., 2016).

Vietnam is especially vulnerable to the effect of climate change because of its geography and population demographics. A report from the Asian Development Bank (ADB, 2009) concluded that many of the countries of Southeast Asia are especially vulnerable to the impacts of climate change because of their long coastlines, high concentration of human and economic activity in coastal regions, large and growing populations, and the importance of agriculture as a source of employment and income. Vietnam's vulnerability is high because of its large cities, coastal regions, and high mountain ranges (Albert et al., 2018). Additionally, low-lying river deltas add to its vulnerability and make it one of the most affected countries from adverse climatic stresses, such as flooding, saltwater intrusion, and drought (Dasgupta et al., 2007, 2011). Rural communities that rely on agriculture are some of the most vulnerable populations to climate change because they often have a vulnerable livelihood, reduced adaptive abilities, and live in high-risk areas (Dung and Sharma, 2017). Seventy percent of Vietnam's population lives in rural areas, and around 60% of the rural population relies on agriculture for their incomes (Bergstedt, 2015). The effects of climate change are felt disproportionately by poor households because their livelihoods are more dependent on agriculture than wealthier households (Davies et al., 2009), and climate change decreases agricultural productivity and food security (Iglesias et al., 2011). For example, Jiang et al. (2018) estimate that rice production in Vietnam may see yield reduction of as much as 23% and over 50% over the next two decades for irrigated and rainfed rice, respectively. Increased climate variability will most threaten communities that rely on resources because of their increased vulnerabilities and risk exposure; this is especially true in rural development and agricultural sectors (IPCC, 2012). Climatic stresses will be felt especially hard by agricultural households. There is evidence that these communities are already feeling these effects. A recent study by Trinh et al. (2018), found that farmers in their study are losing 20% of their annual income from agriculture as a result of climate change.

Weather and climate, including rainfall and its timing, the day-to-day high and low temperatures, the frequency, length, and severity of droughts, and basic growing conditions are expected to become more variable for Vietnamese farmers in the near- and long-term future. Studies have forecast increasing average temperatures, sea-level rise, changing precipitation, and increasing drought in regions of Vietnam (Cuong, 2008; IPCC, 2014). IPSONRE (2009) forecast regional climate change, including the three regions covered in our study, the Red River Delta, Central Vietnam, and the Mekong River Delta. Some of these regional forecasts are the same, such as increasing temperature, frequency and intensity of storms, and drought. Other forecasts are variable over regions, Central Vietnam is forecast to have increased rainfall in addition to their seasonal drought, and the Mekong River Delta is forecast to be impacted by increased sea-level rise and salinity intrusion. Sea-level rise of one meter is anticipated to cause severe impacts to the inhabitants of the Mekong River Delta, Red River Delta, and Ho Chi Minh City (MONRE, 2009). In total, between 11 and 25% of the country's population could be directly affected, and GDP losses are estimated to be between 10 and 25% with a one-meter and three-meter increase in sea level, respectively (Dasgupta et al., 2007). Declining agricultural production is anticipated in Vietnam because of direct effects (changes in carbon dioxide availability, precipitation, and temperatures) and indirect effects (reductions in water availability, the transformation of organic matter in soil, increased pest and diseases prevalence, and loss of arable land resulting from the submergence of coastal lands and soil erosion) (World Bank Group and Asian Development Bank, 2020).

With the presence of all these stresses, the Vietnamese government has been proactive in developing climate change policy development. Vietnam, particularly the agricultural and rural development sectors, have developed comprehensive climate change policies with consideration given to adaptation and mitigation (Dung and Sharma, 2017). Examples include the creation of the National Climate Change Strategy in 2011, which lays out strategic objectives to be accomplished by 2050, or the creation of the National Committee on Climate Change created in 2012 (McKinley et al., 2015)[1]. However, there are opportunities for improvement by bringing in more local stakeholders. Dung and Sharma (2017) state that while the Ministry of Agriculture and Rural Development is ahead in developing policy frameworks for climate change adaptation, current systems do not adequately address the private sector, and local community involvement in responses. Similarly, a key informant interview from McKinley et al. (2015) finds that policy still follows a top-down approach, with almost no consultation with local communities or organizations. Phuong et al. (2018) find that when working in this hierarchical governance system, any effort to support smallholders must be expanded to also engage in policy capacity to ensure efforts are successful. However, Christoplos et al. (2017), bring attention to transformations in climate change adaption in Vietnam that sees local governments playing more important roles in climate change risk reduction—arguing that the role of local government is changing and becoming more responsive facing climate risks. Comprehensive policies with guiding rules to increase the participation of local communities and mechanisms to incentivize them to take part in climate change mitigation and adaptation are essential (Dung and Sharma, 2017). Vietnam has several mitigation options available in agriculture, such as coffee intercropping, use of biochar in maize or rice, and the irrigation technique of alternate wetting and drying in rice production (Escobar Carbonari et al., 2019). Still, climate change is already occurring regardless of how much mitigation is achieved, and moving toward climate change adaptation is urgent and necessary (Owen, 2020). Adaptation and mitigation are not alternatives and must both be pursued, but the costs will influence the choice of policies (Mendelsohn, 2012).

There are numerous climate change adaptations[2], falling into different categories and at varying costs. A recent study by Christoplos et al. (2017) finds that Vietnamese farmers' adaptations are increasingly autonomous and less capital intensive. Autonomous adaptations[3] are not conscious

[1]See McKinley et al. (2015) and Dung and Sharma (2017) for recent reviews of climate change policies in Vietnam.

[2]Climate change adaptation is commonly defined as an adjustment in natural or human systems in response to actual or expected climate stimuli or their effects, which moderates harm or exploits beneficial opportunities (IPCC, 2018; UNFCCC, 2020).

[3]See Malik et al. (2010) for a review of autonomous adaptations.

adaptations to climatic stimuli, but spontaneous responses triggered by changes in natural, market, or human systems (IPCC, 2018). Autonomous adaptations are widely considered to be reactive and undertaken by private actors instead of governments (Malik et al., 2010). Individuals only adopt private adaptations when they are efficient, i.e., when the benefits outweigh the costs, because all of the costs and benefits go to the individual who is making the decision (Mendelsohn, 2000, 2012). Autonomous responses are more often short-run adaptations because the impacts are less uncertain, and benefits are more predictable (Stern, 2007). Long-run are less common than short-run adaptations because of the uncertainty and more substantial capital investments involved in long-term investments (Stern, 2007).

Individuals will make efficient adaptations if they have the resources to do so, but unexpected stress can lead to disruptions in livelihoods, resulting in increased vulnerability from reduced access to social, political, and economic resources (Adger, 1999). Microfinance has the potential to play a significant role in autonomous adaptations by providing households with access to necessary resources (Malik et al., 2010). Agrawala and Carraro (2010) note in their review that the nature of microfinance lending, large volume, and low-value loans is consistent with the needs for adaptation—providing large volumes of decentralized loans. Their review found that significant overlaps already exist between climate change adaptation and microfinance lending. Hammill et al. (2008) argue that microfinance builds resiliency in households by making them less vulnerable to shocks from climatic stresses and more capable of coping with the impacts; as they put it, "the logic here is simple—the more assets and capabilities people have, the less vulnerable they are."

We are not the first researchers interested in how agricultural households are adapting to climate change in Vietnam. There have been numerous studies about varying topics within climate change responses in Vietnam. Using two villages in central Vietnam, Nguyen et al. (2013) developed a framework to assess rural smallholders' vulnerability and argued rice and other rainfed crops were much more affected by extreme drought or floods compared to tree-based systems and argue for increasing resiliency through adding tree crops. Le Dang et al. (2014), interviewed farmers in the Mekong River Delta, using psychological variables to determine adaptations. They find that farmers are more likely to have an adaptive intention if they perceive higher risks and greater effectiveness of adaption measures. McElwee et al. (2017) looked at perceptions of flooding and flood risk reduction measures across income classes of smallholder farmers in the Red River Delta. They find that poor houses were not less proactive in taking flood risk mitigation measures. Trinh et al. (2018) used a multivariate probit model to investigate determinants of farmer adaptation in Ha Tinh Province. They found that attending agricultural production training, gender, and access to credit (and other socioeconomic variables) were the largest determinants. They also find that some of the most common responses were changing crop varieties, monitoring weather forecasts, and adjusting planting times were some of the most common adaptations in central Vietnam. Waibel et al. (2018) conduct a cross-country study in Vietnam and Thailand to determine if perceptions of climate change are linked to farmers taking adaptive measures. While the answer was yes for both countries, the results for Vietnam are more convincing. Likely a result of more frequent climate-related weather shocks in Vietnam. Lastly, Ylipaa et al. (2019) used focus group discussion in Thai Binh Province to investigate gender inequality in climate change adaption.

Additionally, there have been two studies published that used subsets of the same dataset that we use in our analysis. Mishra and Pede (2017) investigated intra-household gender differences in adaptions to climatic stress for farming households in the Mekong River Delta. They conclude that there are intra-household disparities in responses but leave it to future studies to offer a detailed explanation of these differences. Duffy et al. (2020) use data from the Mekong and Red River Deltas and look primarily at the impacts of farm size and the total number of observed climatic stresses on adaptations.

The intentions of previous publications are generally the same as ours, to provide insights to policymakers in an effort to strengthen climate change policy in Vietnam. However, methods and research questions vary widely across studies, with the most similar study to our own coming from Trinh et al. (2018). While the previous literature adds to the discussion in a meaningful way, we believe that gaps in knowledge still exist and that our novel study fills some of these voids. Namely, we are the first to compare autonomous adaptations across three distinct regions in Vietnam, north, south, and central, using the same survey instrument. Furthermore, while most previous work has investigated a single stress, or climatic stress more generally, we are the first to use a robust dataset to investigate multiple stresses and multiple responses simultaneously. This approach allows us to identify which stresses elicit specific responses from individuals, where gaps exist in responses, and how these responses vary across regions. The purpose of this study is to investigate how climate change adaptation in rice-producing households of Vietnam vary, depending on the primary climate stresses and resulting impacts observed by individuals, where gaps exist in responses, and how these responses vary across regions. These results help policymakers in Vietnam design more targeted and effective government responses by describing what farmers are already doing in response to climatic stress, which stress(es) farmers are most responsive to, and how this varies by location. Modeling multiple responses to numerous climatic stresses is a complicated procedure, but it more realistically captures the decision-making process of smallholder farmers in Vietnam. They experience numerous climatic stimuli and make a series of autonomous adaptation decisions in response to those stimuli.

METHODS AND DATA

Data Collection

Data for this study come from household interviews conducted by the International Rice Research Institute with their local partners in Vietnam; the Institute of Policy and Strategy for Agriculture and Rural Development (IPSARD), and the Vietnam National University of Agriculture (VNAU) as part of the Consultative Group on International Agricultural Research Program on Climate Change, Agriculture, and Food Security. The data collection occurred in three rounds of surveys, with IPSARD overseeing the collection occurring in the Mekong River Delta in early 2015 (succeeding the main rice season), and VNAU overseeing the collecting in the Red River Delta and central Vietnam in mid-2016 (succeeding the winter-spring rice season). These three survey rounds are inclusive of seven provinces of Vietnam; An Giang ($n = 180$), Bac Lieu ($n = 128$), Ha Tinh ($n = 224$), Nam Dinh ($n = 210$), Quang Ngai ($n = 226$), Thai Binh ($n = 218$), and Tra Vinh ($n = 120$). The survey resulted in a total of 1,306 unique respondents, comprised of husbands and wives from 653 rice-producing households. Missing responses for the key choice variables reduced the number of observations used to 1,290 for the household choice model and 1,244 for the agricultural choice model.

The surveyed provinces in this study were selected based on previous knowledge of climate change issues in each location. The same criteria were used to then select communes, districts, and villages. Once a final selection of villages was determined, the village head (or similar) provided a list of farmers with a household head with at least 10 years of rice-farming experience to the enumerators. Survey participants were then selected from the line lists provided for each village using a stratified random sampling procedure with equal numbers of respondents from each village. Enumerators conducted face-to-face interviews at the respondents' households. Informed verbal consent was obtained from each participant, and then husbands and wives of each household were interviewed privately while their spouses waited in a location in which they could not hear the interview. The survey collected socioeconomic data for each household before moving on to specific questions related to climate stress, impacts of this stress, and individual responses to climatic stress.

Data Description

We are primarily interested in how individual responses vary, depending on which climatic stress most affects each respondent and which impacts are brought on by the reported stress. Enumerators asked the respondents to consider changes in climatic stress and resulting impacts and adaptations from the previous 10-year period, hence why only farming households with at least one household member with 10 or more years of experience were interviewed. We look at two levels of autonomous adaptations from this period. For the household level, we use responses to the question, "What coping strategies do you do in response to the negative impacts of this stress?" and for the agricultural level, we use responses to the question, "What changes in your farming activities did you do during this stress?" We argue for causality in these responses because of the structure of the survey. The questionnaire asks respondents to identify all climatic stresses that are present in their area and then identify the one that most affects them from a list of stresses, previously identified to be present in Vietnam. The definition of these stresses and their material impact on rice production are:

- *Flooding* is extended periods of excessive rainfall, beyond the normal limits for a region. Rice crops exposed to flooding for prolonged periods can fail.
- *Storms* are disturbances in the atmosphere that result in periods of strong winds and heavy rainfall. Heavy winds can destroy rice plants in the paddy through lodging, and sudden rainfall from storms can erode soil and destroy crops.
- *Salinity intrusion* is the movement of seawater inland into freshwater aquifers and rice paddies. When soils become too saline from saltwater intrusion, they are no longer suitable to grow rice.
- *Sea-level rise* is an increase in global sea level, which encroaches into low-lying coastal lands. Suitable agricultural land can be lost to the encroaching sea, or farmers may be forced to invest in expensive infrastructure to protect low-lying coastal lands.
- *Drought* is a shortage of water resulting from an extended period of low rainfall. Periods of drought can increase rice farmers' irrigation costs or even result in total crop failure when irrigation is either not available or too costly.
- *Heat* is extended periods of above-average temperatures. High temperatures, particularly during the flowering period, can cause low yields or total crop failure in rice plants, as a result of spikelet sterility.

All succeeding questions refer to the response for stress that most affects them, including the resulting impacts and autonomous adaptations. Respondents reported which impacts they experienced as a result of the climatic stress by answering a series of binary yes-no questions to signify that the stress caused any of the following impacts—decreases in rice paddy yield, or increases in rice crop loss (e.g., crop destroyed from lodging), food insecurity, indebtedness, or detrimental health impacts.

We model the causal structure of decision making as follows:

Perceived climatic stress → resulting impacts/outcomes → reported autonomous adaptations

Because respondents could have multiple reported responses to climate change, we model their choices using a multivariate probit model. This model allows us to jointly estimate several correlated outcomes simultaneously, and we expect that responses to changing climatic stimuli are correlated. To make the use of this model feasible, we clustered the original responses for the household and the agricultural models into aggregate groups. The group aggregates and the corresponding disaggregate responses are in **Appendix 1** and **2** in **Supplementary Material** for the household and agricultural models, respectively. This step is necessary because multivariate probit models produce 2^n choice regimes, where $n =$ the number of dependent variables jointly modeled. There were 14 possible original options (i.e., dependent variables) for the household model, which results in an unmanageable problem where there are 2^{14} or 16,384 choice regimes.

Multivariate Probit Estimation

The applications in this study estimate a set of multivariate probit choice models. Unlike other discrete choice models, such as multinomial logit and generalized extreme value distributions, multivariate probit models allow random preferences across agents, general correlations across simultaneous choices, and unrestricted substitution patterns between those choices (Train, 2009). These are all relevant and important properties of the choice framework for this study.

Any multivariate discrete choice model presents several complications with respect to robust and precise estimation of the unknown model parameters. This is especially true for problems with multiple choice dimensions. These kinds of problems inevitably result in multiple integrals over a probability space, generally without any closed form expression or simple mechanism to evaluate or approximate these integrals. This leads to a need for repeated calculations of approximations to these integrals at each iteration while one estimates the unknown structural parameters of the model. This study employs a fully-developed approach that is well-understood and well-accepted in the econometrics of limited dependent variable models that is known to be computationally efficient (i.e., requires a minimum number of calculations), is accurate (unbiased and consistent), and precise (efficient).

The current industry standard for estimating multivariate limited dependent variable (LDV) models such as the multivariate probit proceeds in two important steps. The first reduces the modeling problem through a set of mathematical transformations to one that is bounded on the multivariate unit interval, $[0,1]\times\cdots\times[0,1]=[0,1]^N$ The canonical derivation of these reductions is presented in Genz (1993). We reproduce and briefly discuss these mathematical steps for the case of $N = 3$. The statistical model is based on the system of latent variables,

$$y_{ij}{}^{*} = \boldsymbol{x}_i{}'\boldsymbol{\beta}_j + \varepsilon_{ij},\ i=1,\ldots,I,\ j=1,\ \ldots,\ N,\ \boldsymbol{\varepsilon_{ij}} i.i.d.N\left(0_N,\boldsymbol{R}\right),$$

$$\boldsymbol{R} = \begin{bmatrix} 1 & \rho_{12} & \ldots & \rho_{1N} \\ \rho_{12} & 1 & \ldots & \rho_{2N} \\ \vdots & \ddots & \ddots & \vdots \\ \rho_{1N} & \ldots & \rho_{N-1,N} & 1 \end{bmatrix}, \quad (1)$$

and the associated observable indicator variables,

$$y_{ij} = \begin{cases} 0,\ \textit{iff}\ y_{ij}^{*} \le 0,\ \textit{iff}\ \varepsilon_{ij} \le -\boldsymbol{x}_i{}'\beta_j, \\ 1,\ \textit{iff}\ y_{ij}^{*} > 0,\ \textit{iff}\ \varepsilon_{ij} > -\boldsymbol{x}_i{}'\beta_j, \end{cases} i=1,\cdots,I,\ j=1,\cdots,N. \quad (2)$$

The multivariate probit model estimates the probability that each respondent's choices fall in the appropriately associated regime. The probit model estimates the correlation matrix, $\boldsymbol{R}$, and normalized slope coefficients, β_j, as necessary and sufficient conditions for identification.

For $N = 3$, let $\mathcal{R} = \{0,1,2,3,4,5,6,7\}$ be the set of choice regimes and associate each $r\in\mathcal{R}$ as follows with the percent corresponding to each regime in parentheses.

Household model:

$$r_i = \begin{cases} 0,\text{ no adaptation},\ y_{i1}=y_{i2}=y_{i3}=0 & (53\%) \\ 1,\text{ financial response},\ y_{i1}=1, y_{i2}=y_{i3}=0 & (9\%) \\ 2,\text{ lifestyle adjustment},\ y_{i2}=1, y_{i1}=y_{i3}=0 & (17\%) \\ 3,\text{ outside assistance},\ y_{i3}=1, y_{i1}=y_{i2}=0\ (2\%) & \\ 4,\text{ financial response \& lifestyle adjustment}, & \\ y_{i1}=y_{i2}=1, y_{i3}=0 & (11\%) \\ 5,\text{ financial response \& outside assistance}, & \\ y_1=y_3=1, y_2=0 & (2\%) \\ 6,\text{ lifestyle adjustment \& outside assistance}, & \\ y_{i1}=0, y_{i2}=y_{i3}=1 & (2\%) \\ 7,\text{ all 3 adaptations},\ y_{i1}=y_{i2}=y_{i3}=1 & (4\%) \end{cases} \quad (3)$$

Agricultural model:

$$r_i = \begin{cases} 0,\text{ no change},\ y_{i1}=y_{i2}=y_{i3}=0 & (36\%) \\ 1,\text{ rice change},y_{i1}=1, y_{i2}=y_{i3}=0 & (6\%) \\ 2,\text{ crop change},\ y_{i2}=1, y_{i1}=y_{i3}=0 & (35\%) \\ 3,\text{ livestock change},\ y_{i3}=1, y_{i1}=y_{i2}=0 & (1\%) \\ 4,\text{ rice change \& crop change}, & \\ y_{i1}=y_{i2}=1, y_{i3}=0 & (16\%) \\ 5,\text{ rice change \& livestock change}, & \\ y_1=y_3=1, y_2=0 & (0\%) \\ 6,\text{ crop change \& livestock change}, & \\ y_{i1}=0, y_{i2}=y_{i3}=1 & (5\%) \\ 7,\text{ all 3 adaptations},\ y_{i1}=y_{i2}=y_{i3}=1 & (3\%) \end{cases} \quad (4)$$

The estimation problem is to find values of $(\beta_1,\cdots,\beta_N,\boldsymbol{R})$ to maximize the joint likelihood, or probability, of the survey respondents' falling in the associated reported regimes. Genz's (1993) procedure follows a sequence of recursive changes in variables to the associated probability integrals compactly and conveniently for each respondent. First, define the lower triangular Cholesky factorization of the correlation matrix by $\boldsymbol{R} = \boldsymbol{LL}'$, where $\boldsymbol{L}$ is a lower triangular matrix with strictly positive main diagonal elements, i.e., for the case of $N = 3$,

$$\boldsymbol{L} = \begin{bmatrix} \ell_{11} & 0 & 0 \\ \ell_{21} & \ell_{22} & 0 \\ \ell_{31} & \ell_{32} & \ell_{33} \end{bmatrix},\ \ell_{11},\ell_{22},\ell_{33} > 0. \quad (5)$$

Second, define the *i.i.d.* standard normal random variables, $\boldsymbol{z_{ij}}\ iid\ N(0_3,\boldsymbol{I}_3)$, by the system of linear equations, $\varepsilon_{ij} = \boldsymbol{Lz}_{ij}$, so that $(\varepsilon_{ij}) = \boldsymbol{L}E(\boldsymbol{z}_{ij}) = 0_3$, and $(\varepsilon_{ij}\varepsilon_{ij}{}') = \boldsymbol{L}E(\boldsymbol{z}_{ij}\boldsymbol{z}_{ij}{}')\boldsymbol{L}' = \boldsymbol{R}, \forall\ i = 1,\cdots,I$. This implies the recursive structure for the standard normal random variables:

$$\varepsilon_{ij} = \sum_{k=1}^{j}\ell_{jk}z_{ik} \le -\boldsymbol{x}_i{}'\beta_j, \textit{iff}\ z_{ij} \le -\frac{\left(\boldsymbol{x}_i{}'\beta_j + \sum_{k=1}^{j-1}\ell_{jk}z_k\right)}{\ell_{jj}}$$
$$i=1,\cdots,I,\ j=1,\cdots,N. \quad (6)$$

This gives the probability that the i^{th} survey respondent chooses regime $r_i \in \mathcal{R}$ in terms of a recursive set of standard normal integrals, with the limits of integration functions of the lower indexed levels of the standard normal random variates. For example, for $r_i = 0$ we have

$$Pr\left(r_i = 0\right) = \int_{-\infty}^{-\frac{x_i'\beta_1}{\ell_{11}}} \left(\int_{-\infty}^{-\frac{(x_i'\beta_2+\ell_{21}z_1)}{\ell_{22}}} \left(\int_{-\infty}^{-\frac{(x_i'\beta_3+\ell_{31}z_1+\ell_{32}z_2)}{\ell_{33}}} \varphi(z_3)dz_3 \right) \varphi(z_2)dz_2 \right) \varphi(z_1)dz_1, \quad (7)$$

where $\varphi(z) = \frac{1}{\sqrt{2\pi}} e^{-z^2}$ is the standard normal probability density function (pdf). The other seven regimes have analogous probability statements with the upper (lower) limits of integration defined by $-\left(\boldsymbol{x}_i'\beta_j + \sum_{k=1}^{j-1} \ell_{jk} z_k\right)/\ell_{jj}$ if $y_{ij} = 0, (1)$, for each $j = 1, 2, 3$. If $y_{ij} = 0$, then the lower limit of integration is $-\infty$, while if $y_{ij} = 1$, then the upper limit of integration is $+\infty$.

These unbounded limits of integration in all cases lead to difficulties in approximating these multivariate probability statements, whether this is done through quadrature or some other means of estimation. Consequently, Genz (1993) and others (Geweke, 1989, 1991; Hajivassiliou, 1993; Keane, 1993, 1994; Hajivassiliou and Ruud, 1994; McFadden and Ruud, 1994; Hajivassiliou et al., 1996; Hajivassiliou and McFadden, 1998) recursively transform the standard normal random variables to the uniform distribution by,

$$u_{ij} = \Phi(z_{ij}) = \int_{-\infty}^{z_{ij}} \varphi(z)dz, \; du_{ij} = \varphi\left(z_{ij}\right) dz_{ij}, \\ z_{ij} = \Phi^{-1}(u_{ij}), \; i = 1, \cdots, I, \; j = 1, \cdots, N, \quad (8)$$

where $\Phi(z) = \int_{-\infty}^{z} \frac{1}{\sqrt{2\pi}} e^{-x^2} dx$ is the cumulative distribution function (cdf) of the standard normal random variable.

If $y_{ij} = 0$, then set the lower limit of integration for u_{ij} to $\underline{U}_{ij} = 0$ and the upper limit of integration for u_{ij} to $\bar{U}_{ij} = \Phi\left(-\frac{\left(\boldsymbol{x}_i'\beta_j + \sum_{k<j} \ell_{jk}\Phi^{-1}(u_{ik})\right)}{\ell_{jj}}\right)$. On the other hand, if $y_{ij} = 1$, then set the lower limit of integration to $\underline{U}_{ij} = \Phi\left(-\frac{\left(\boldsymbol{x}_i'\beta_j + \sum_{k<j} \ell_{jk}\varphi^{-1}(u_{ik})\right)}{\ell_{jj}}\right)$ and the upper limit of integration to be $\bar{U}_{ij} = 1$. Accurate and fast algorithms are available to evaluate the standard normal cdf (Hastings, 1995) and its inverse (Acklam, 2010).

In each individual survey response and at every level of integration, dependence of the sequential limits of integration on $\boldsymbol{x}_i$, $[\boldsymbol{\beta_1} \;\; \boldsymbol{\beta_2} \;\; \boldsymbol{\beta_3}]'$, $\boldsymbol{L}$, and uniform random variables $[u_{i1} \; \cdots \; u_{i,j-1}]'$ is taken into account explicitly to evaluate and update the likelihood function. However, there remains the additional complication of repeatedly, accurately, and quickly evaluating the multidimensional probability integrals in the multivariate probit model. This is the focus of the second major step in the estimation process, developed and analyzed independently by Geweke (1989, 1991), Hajivassiliou (1993), and Keane (1993, 1994). This step uses unbiased simulations of the unknown probabilities and their derivatives with respect to the estimated parameters in each regime. By construction, these probability simulations are unbiased in each replication. Letting the number of simulations be denoted by S and the probability of a given regime $r \in \mathcal{R}$ be denoted by P_r, the simple arithmetic average of S independent simulations also is unbiased and has variance $P_r(1-P_r)/S$, a small number for reasonably large values of S, since $0 < P_r\left(1-P_r\right) \leq \frac{1}{4}$, i.e., 100 simulations for each multivariate probability integral has a variance that is bounded from above by 1/400.

This particular simulation method is commonly known as the GHK "importance sampling" algorithm, to denote the developers Geweke, Hajivassiliou, and Keane. This and many other simulation methods have received a great deal of detailed theoretical and empirical analysis, with noteworthy studies by McFadden (1989); Hajivassiliou and Ruud (1994); McFadden and Ruud (1994); Hajivassiliou et al. (1996); Hajivassiliou and McFadden (1998); Train (2009). The overarching conclusion of these studies is that the GHK algorithm is the most accurate and computationally efficient method to estimate a wide range of LDV models. From the unbiased and precise simulated probability estimates, the invariance principle for maximum likelihood estimators is invoked to generate consistent and asymptotically normal estimators of the structural parameters, $\boldsymbol{B}, \boldsymbol{\Sigma}$, and their asymptotic (i.e., large sample) standard errors.

For our study, the individual choice probability, or likelihood function, is given by

$$L_i(\boldsymbol{x}_i, \beta, \boldsymbol{L}) = Pr(r = r_i) = \int_{\underline{U}_{i1}}^{\bar{U}_{i1}} \int_{\underline{U}_{i2}}^{\bar{U}_{i2}} \int_{\underline{U}_{i3}}^{\bar{U}_{i3}} du_3 du_2 du_1. \quad (9)$$

Each joint integral is over a proper subset of the 3-dimensional unit cube, $[0,1] \times [0,1] \times [0,1]$, so that this can be evaluated quickly and precisely with any number of methods. The current industry standard is simulation methods. There is no limit to the number of discrete choices, in principle. However, the curse of dimensionality increases computational time rapidly as the dimension of a problem grows, even with modern computing speeds and power. The full likelihood function for all survey respondents is

$$\prod_{i=1}^{I} L_i(\boldsymbol{x}_i, \beta, \boldsymbol{L}) = \prod_{i=1}^{I} \left(\int_{\underline{U}_{i1}}^{\bar{U}_{i1}} \int_{\underline{U}_{i2}}^{\bar{U}_{i2}} \int_{\underline{U}_{i3}}^{\bar{U}_{i3}} du_3 du_2 du_1 \right). \quad (10)$$

The method simulates the likelihood function for each given $(\boldsymbol{x}_i, \beta, \boldsymbol{L})$ to approximate the integrals on the right-hand-side, and searches of the parameters $(\beta, \boldsymbol{L})$ to find the simulated maximum likelihood estimators.

A complete list of independent variables with summary statistics is in **Table 1**, and descriptions of the variables are in **Appendix 3** in **Supplementary Material**.

TABLE 1 | Summary statistics of independent variables.

Variable	Mean	Std. Dev.	Min	Max
Flood stress	0.27	0.44	0.00	1.00
Storm stress	0.17	0.38	0.00	1.00
Salinity stress	0.17	0.38	0.00	1.00
Drought stress	0.16	0.36	0.00	1.00
Heat stress	0.16	0.36	0.00	1.00
Other stress	0.01	0.11	0.00	1.00
No stress	0.07	0.25	0.00	1.00
Low yield	0.70	0.46	0.00	1.00
Crop loss	0.24	0.43	0.00	1.00
Food insecurity	0.05	0.22	0.00	1.00
Increased debt	0.06	0.24	0.00	1.00
Health impact	0.84	0.36	0.00	1.00
No impact	0.14	0.35	0.00	1.00
Male	0.50	0.50	0.00	1.00
Age (years)	51.17	10.91	22.00	86.00
Education (years)	6.62	2.74	0.00	14.00
Farm experience (years)	31.50	11.10	2.00	63.00
Total household size	4.08	1.56	2.00	10.00
Total farm size (ha)	0.99	1.30	0.05	14.30
An Giang Province	0.14	0.34	0.00	1.00
Bac Lieu Province	0.10	0.30	0.00	1.00
Ha Tinh Province	0.17	0.38	0.00	1.00
Nam Dinh Province	0.16	0.37	0.00	1.00
Quang Ngai Province	0.17	0.38	0.00	1.00
Tra Vinh Province	0.09	0.29	0.00	1.00
Thai Binh Province	0.17	0.37	0.00	1.00
Total HH income (million VND)	129.83	144.71	2.25	1,760.00
Ag info—government	0.37	0.48	0.00	1.00
Ag info—radio	0.18	0.38	0.00	1.00
Ag info—television	0.34	0.47	0.00	1.00
Ag info—traditional	0.28	0.45	0.00	1.00
Ag into—neighbor	0.18	0.38	0.00	1.00
Ag info—another farmer	0.17	0.38	0.00	1.00
Weather info—government	0.15	0.36	0.00	1.00
Weather info—radio	0.30	0.46	0.00	1.00
Weather info—television	0.87	0.33	0.00	1.00
Weather info—traditional	0.21	0.41	0.00	1.00
Weather info—neighbor	0.13	0.33	0.00	1.00

RESULTS AND DISCUSSION

Climatic Stresses

The provinces surveyed in this study face varied and unique climatic stress. Of those mapped in **Figure 1**, the most notable result is that very few farmers reported no stress present in their areas. Provinces in the Red River Delta had the highest percentage of no-stress-present responses with 10 and 13% for Thai Binh and Nam Dinh, respectively. However, all other provinces only reported between 1 and 2% that there is no stress present in their area. Climatic stresses are observed widely across the entire country. These results provide empirical evidence in support of climate change vulnerability mapping done by Yusuf and Francisco (2009), which forecast high vulnerability to climate change in all three regions of our study.

Some stresses are reported more homogenously across the country, while others impact individual provinces much more than others. Heat stress is reported more uniformly across provinces by anywhere from one-half to three-quarters of respondents in each province. Drought is frequently reported in all provinces as well, although less frequently in the Red River Delta, where only one-quarter of all respondents report its presence. Other surveyed provinces report drought more frequently, between 41 and 89% of the time. Individuals report the remaining stresses more heterogeneously. Respondents commonly cite flooding in Central Vietnam and An Giang Province, but less so in the Red River Delta and the coastal provinces of the Mekong River Delta. They also report storms least frequently in the Mekong River Delta compared to other locations. Finally, salinity and sea-level rise are more common in low-lying coastal regions. For example, An Giang province is comfortably inland, and nobody from this province reported the presence of either sea-level rise or salinity. Some climatic stresses are felt homogenously across Vietnam, but others vary significantly from one province or region to another.

Household Adaptations

We begin by looking at the autonomous responses to climatic stress at the household level to determine if specific climatic stresses and their impacts are eliciting stronger or more varied responses from individuals. The results of the multivariate probit model for household adaptations are available in **Table 2**[4].

We find variations in the type of responses and likelihoods of individuals choosing a specific adaptation depending on the stress that most affected them. Flood and drought stresses elicit the strongest responses. Drought is a significant factor in selecting both financial and lifestyle changes. Flood stress is only a significant factor for financial change, but it has the largest coefficient and highest level of significance among all the stresses. Storm and salinity stresses are also significant factors for individuals choosing a financial change, but only at the 10% level of significance. Individuals responded the least to heat stress in their adaptation decisions. Heat stress is only a significant factor for a lifestyle change adaptation, and it reduced the likelihood of an individual choosing that option. Whether an individual has an autonomous response varies by the type of stress that most affects them.

A financial response is the most common autonomous adaptation selected as a result of stress. The likelihood of a financial response increased for all stresses, except for drought. Additionally, increased debt as an impact of stress correlates with financial response. This unsurprising result is likely from individuals borrowing money as an adaptation strategy; the adaptation is worsening the impact. The popularity of financial

[4]Some responses at the household level of adaptation were ambiguous. **Table 2** includes these ambiguous responses as part of the outside option. An alternative specification that omits ambiguous responses is in **Appendix 4** in **Supplementary Materials**. Similar results are obtained in both specifications of the model.

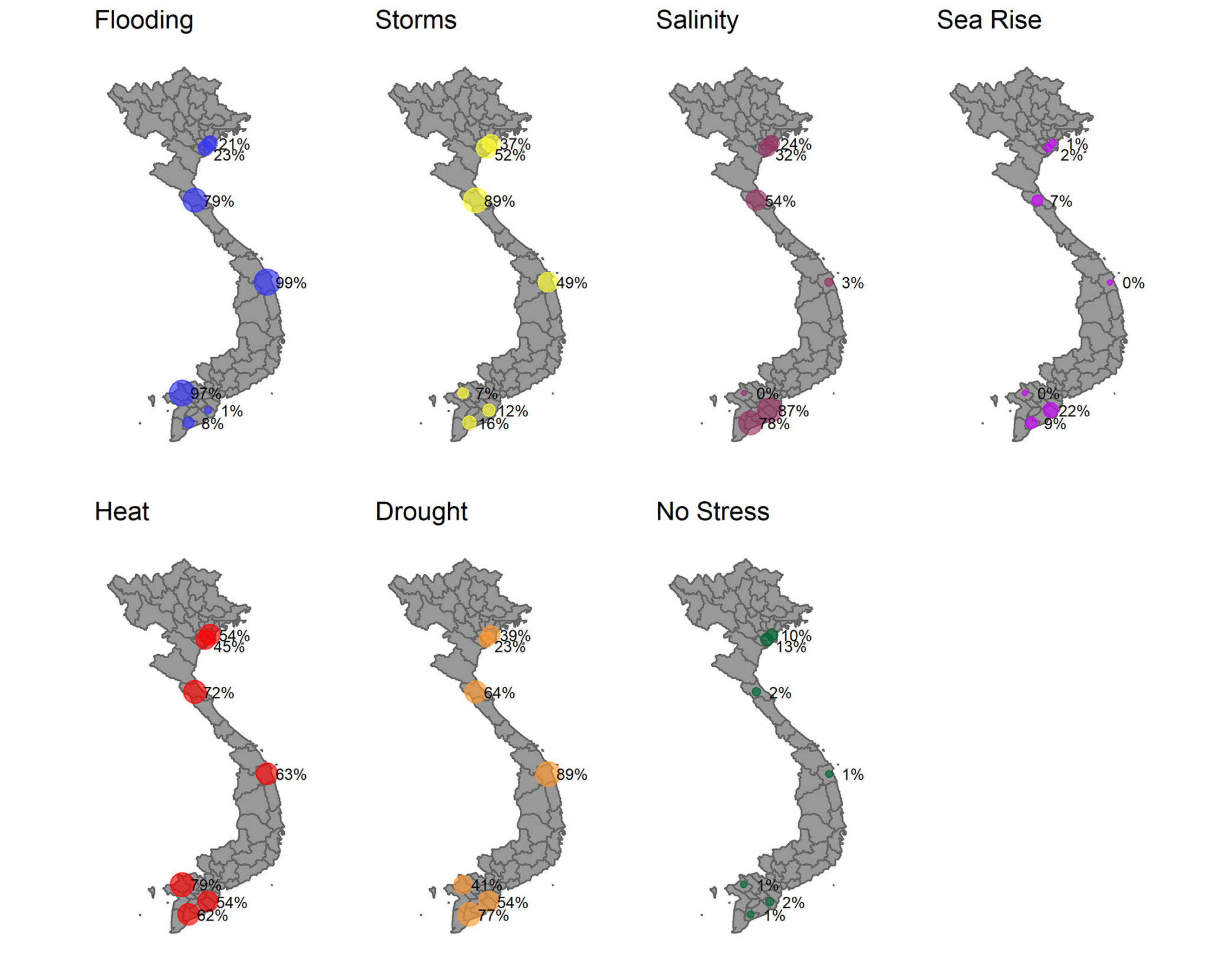

FIGURE 1 | Prevalence of climatic stresses, by province.

adaptations shows the importance of providing affordable credit schemes, such as microfinance, to support the autonomous responses of individuals. Hammill et al. (2008) argue that access to microfinance builds resiliency in households. Furthermore, Mendelsohn (2000, 2012) argues that individuals only make efficient adaptations where the benefits outweigh the costs. Supporting these financial adaptations can improve the efficiency of autonomous responses because it decentralizes decisions to make them more site- and individual-specific.

Drought and heat stress also significantly affected whether or not an individual chose a lifestyle adjustment, albeit only at the 10% level of significance. Drought made an individual more likely to make a lifestyle adjustment, and heat made an individual less likely to make a lifestyle adjustment. Lifestyle adjustments are understandably less common than financial adaptations because these short-run adaptations can have long-lasting consequences. For example, the most detrimental (and thankfully least frequently reported) lifestyle adjustment, taking a child out of school, can burden the child with reduced earnings over their entire lifetime. The other two reported lifestyle adjustments, reducing consumption and working more, are more limited than financial responses because of their explicit binding constraints. There is a ceiling on how many hours a person can work per day and a floor on how little they can consume and still survive.

The effects of the impacts brought on by stress vary by reported adaptation. All three responses significantly correlate with increased debt. Reporting a financial change or receiving outside assistance also significantly correlates with experiencing crop loss. None of the other impacts were significant factors in selecting household responses, likely because most of the data collected in the survey are agricultural impacts and not general impacts that the household may experience from climate change.

The map in **Figure 2** provides a spatial representation of where adaptations are happening (or not happening) in Vietnam. The map shows some apparent differences in how individuals in different provinces are adapting to climate change. Generally,

TABLE 2 | Multivariate probit results, individual coping strategies to climate stress.

	(1) Financial Change		(2) Lifestyle Change		(3) Outside Assistance	
	Mean	**St. Error**	**Mean**	**St. Error**	**Mean**	**St. Error**
No stress (base)	–	–	–	–	–	–
Flood stress	0.601***	(0.223)	0.004	(0.199)	0.245	(0.288)
Storm stress	0.400*	(0.236)	−0.076	(0.214)	−0.150	(0.289)
Salinity stress	0.394*	(0.222)	0.290	(0.200)	0.081	(0.250)
Drought stress	0.512**	(0.223)	0.354*	(0.200)	0.142	(0.268)
Heat stress	−0.073	(0.235)	−0.401*	(0.211)	−0.438	(0.306)
Low yield	−0.005	(0.132)	−0.027	(0.129)	0.183	(0.169)
Crop loss	0.244**	(0.101)	−0.026	(0.099)	0.265**	(0.126)
Food insecurity	−0.019	(0.207)	−0.186	(0.198)	−0.341	(0.276)
Increased debt	0.514***	(0.180)	0.634***	(0.171)	0.392**	(0.191)
Health impact	−0.198	(0.180)	−0.150	(0.171)	0.308	(0.244)
No impact	0.185	(0.134)	0.077	(0.127)	0.150	(0.165)
Male	−0.270***	(0.086)	0.160*	(0.082)	−0.072	(0.109)
Age (years)	−0.001	(0.008)	−0.008	(0.007)	−0.009	(0.009)
Education (years)	0.003	(0.016)	0.019	(0.016)	0.017	(0.020)
Farm experience (years)	−0.003	(0.007)	0.001	(0.007)	0.008	(0.009)
Total household size	0.066**	(0.029)	0.041	(0.028)	0.045	(0.036)
Total farm size (ha)	0.130**	(0.051)	0.021	(0.048)	0.106	(0.065)
An Giang province (base)	–	–	–	–	–	–
Bac Lieu province	0.384*	(0.200)	0.129	(0.198)	1.148***	(0.279)
Ha Tinh province	−0.485**	(0.191)	−0.087	(0.182)	0.083	(0.295)
Nam Dinh province	−0.494**	(0.211)	−0.698***	(0.207)	0.769**	(0.302)
Quang Ngai province	−0.762***	(0.182)	0.022	(0.172)	0.302	(0.258)
Tra Vinh province	0.159	(0.218)	−0.041	(0.212)	1.399***	(0.298)
Thai Binh province	−0.401**	(0.199)	−0.449**	(0.193)	0.416	(0.294)
Total HH income (million VND)	−0.001***	(0.000)	−0.000	(0.000)	−0.001*	(0.001)
Ag info—government	−0.032	(0.104)	0.103	(0.098)	0.138	(0.137)
Ag info—radio	0.120	(0.118)	0.538***	(0.113)	−0.138	(0.153)
Ag info—television	−0.158	(0.096)	0.134	(0.091)	0.282**	(0.122)
Ag info—traditional	0.313***	(0.107)	0.562***	(0.101)	0.206	(0.136)
Ag into—neighbor	−0.134	(0.128)	0.109	(0.118)	−0.451***	(0.173)
Ag info—another farmer	0.497***	(0.114)	0.253**	(0.110)	0.228	(0.150)
Weather info—government	−0.078	(0.148)	−0.167	(0.136)	0.200	(0.183)
Weather info—radio	−0.093	(0.098)	0.285***	(0.092)	−0.027	(0.125)
Weather info—television	0.059	(0.147)	−0.166	(0.136)	−0.376**	(0.168)
Weather info—traditional	0.154	(0.122)	0.068	(0.114)	0.098	(0.151)
Weather info—neighbor	−0.349**	(0.145)	0.088	(0.126)	0.044	(0.183)
Constant	−1.107***	(0.380)	−0.711**	(0.353)	−2.258***	(0.488)
ρ_{21}	0.399***	(0.059)				
ρ_{31}	0.457***	(0.076)				
ρ_{32}	0.275***	(0.073)				
Observations	1,290		1,290		1,290	

****, **, and * are significant at 1, 5, and 10% respectively.*

fewer adaptations occurred in the Red River Delta and reported adaptations increased farther south in Vietnam. In the Red River Delta, provinces report no change as an adaptation to climate change most frequently, 70 and 71% for Thai Binh and Nam Dinh, respectively. This response is substantially higher than any of the other adaptation options for the region Respondents from the Red River Delta are using fewer autonomous responses than the other regions of the study.

The Mekong River Delta, and especially the coastal provinces, were the most responsive to climate change. These results from **Figure 2**, in concert with results from **Figure 1**, provides some empirical support to Le Dang et al. (2014) that perception of

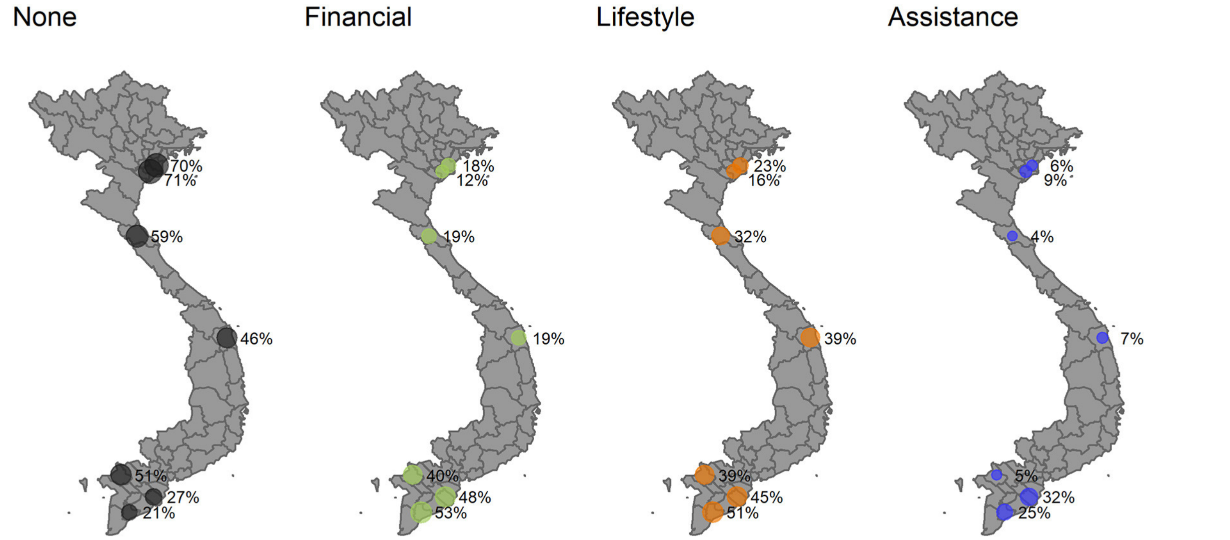

FIGURE 2 | Map showing the percent of respondents practicing household adaptations in each surveyed province.

risk drives adaptive intentions. The provinces reporting the most stresses also report the most adaptations. Bac Lieu and Tra Vinh reported the highest percentage of respondents who practice financial changes, lifestyle changes and receive outside assistance. An Giang reported similar values for financial and lifestyle changes but reported receiving assistance much less than the coastal provinces of the Mekong River Delta. The results show that even within the same region, adaptation strategies can vary considerably.

Agricultural Adaptations

A multivariate probit model is also used to analyze autonomous responses to climatic stress through agricultural adaptations. This level of adaptation is similar to the study from Trinh et al. (2018) conducted in Ha Tinh province. The results of this multivariate probit model are in **Table 3**[5]. Agricultural adaptations are much less responsive to specific climatic stresses than household responses were in the previous section. Instead, individuals are more responsive to the impacts resulting from stress than which stress caused the impact. Only heat elicits a response at the agricultural level. Individuals who report heat stress are more likely to adapt using a crop change on their farm and less likely to adapt by moving resources into livestock production and away from rice production. While moving into livestock was a popular response in some cases, the negative coefficient signals that livestock is also susceptible to heat stress and therefore not a suitable response to this climatic stress.

[5]Some responses at the agricultural level of adaptation were ambiguous. **Table 3** includes these ambiguous responses are part of the outside option. An alternative specification that omits ambiguous responses is in **Appendix 5** in **Supplementary Materials**. Similar results are obtained in both specifications of the model.

Adaptations vary, depending on which impact of stress individuals are responding to. Individuals change their rice variety when the resulting impact of the stress is either lower yields or increased debt. Low yield also made individuals more likely to make a crop change. Additionally, individuals made a crop change if they experienced crop loss. Individuals who report food insecurity and increased debt, are both more likely to make a livestock change in which they move away from rice production and into raising livestock. Low yields, crop loss, food insecurity, and increased debt all produce climate change adaptations, but the adaptations vary across the range of impacts.

The three responses to climatic stress estimated in our agricultural model take varying levels of effort from farmers to adopt. For instance, changing from one rice variety to another takes the least effort, as the benefits are embedded in the seed technology, and all other aspects of producing rice remain the same. However, this convenience comes at a price; purchasing rice seed can be expensive compared to other responses. Farmers likely exert more effort with the crop change response because they may need to learn how to grow an unfamiliar crop or invest time to learn about cropping calendars in their regions. Farmers may also face additional costs (e.g., new crops can require new infrastructure) or loss of revenue if they leave lands fallow. Switching from rice to livestock production, particularly for farmers with no previous livestock experience, requires the most effort (e.g., learning about animal health, nutrition, husbandry, etc.) and can also be costly. Not only do farmers have to invest in the livestock, but they may also incur infrastructure costs to accommodate the livestock. The effort and costs associated with these responses help explain the frequency in which farmers report using them (e.g., why switching to livestock is the least common response).

Like the previous section, the map in **Figure 3** provides a spatial representation of where agricultural adaptations are

TABLE 3 | Multivariate probit results, agricultural adaptations to climate stress.

	(1) Rice change		(2) Crop change		(3) Livestock change	
	Mean	St. Error	Mean	St. Error	Mean	St. Error
No stress (base)	–	–	–	–	–	–
Flood stress	0.090	(0.218)	−0.002	(0.191)	−0.253	(0.286)
Storm stress	−0.356	(0.232)	0.056	(0.201)	−0.176	(0.292)
Salinity stress	−0.339	(0.232)	0.073	(0.197)	−0.386	(0.284)
Drought stress	0.028	(0.225)	−0.049	(0.196)	−0.447	(0.286)
Heat stress	−0.045	(0.222)	0.390**	(0.193)	−0.614**	(0.294)
Low yield	0.286*	(0.151)	0.278**	(0.125)	0.252	(0.189)
Crop loss	0.076	(0.107)	0.246**	(0.098)	0.211	(0.136)
Food insecurity	0.207	(0.225)	−0.323	(0.214)	0.857***	(0.240)
Increased debt	0.392*	(0.203)	−0.137	(0.178)	0.530**	(0.247)
Health impact	0.168	(0.188)	−0.219	(0.160)	0.170	(0.255)
No impact	0.186	(0.145)	−0.014	(0.119)	0.163	(0.191)
Male	0.227***	(0.086)	−0.035	(0.078)	0.241**	(0.115)
Age (years)	−0.023***	(0.008)	0.002	(0.007)	−0.013	(0.011)
Education (years)	0.014	(0.018)	0.032**	(0.016)	−0.006	(0.024)
Farm experience (years)	0.015**	(0.008)	−0.003	(0.007)	−0.000	(0.011)
Total household size	−0.017	(0.030)	0.048*	(0.027)	0.118***	(0.037)
Total farm size (ha)	−0.077	(0.057)	0.083*	(0.048)	0.137*	(0.070)
An Giang Province (base)	–	–	–	–	–	–
Bac Lieu Province	−0.364	(0.223)	0.300	(0.190)	0.015	(0.348)
Ha Tinh Province	−0.259	(0.192)	0.206	(0.176)	0.762**	(0.319)
Nam Dinh Province	0.123	(0.204)	0.235	(0.188)	1.259***	(0.329)
Quang Ngai Province	−0.290	(0.186)	0.364**	(0.169)	0.818***	(0.306)
Tra Vinh Province	−0.174	(0.239)	0.281	(0.209)	0.850**	(0.347)
Thai Binh Province	0.197	(0.196)	0.102	(0.181)	1.536***	(0.317)
Total HH income (million VND)	0.000	(0.000)	−0.001**	(0.000)	0.000	(0.001)
Ag info—government	0.203**	(0.102)	0.175*	(0.094)	−0.134	(0.145)
Ag info—radio	0.088	(0.115)	0.032	(0.109)	−0.090	(0.166)
Ag info—television	0.230**	(0.092)	0.041	(0.085)	0.173	(0.125)
Ag info—traditional	0.084	(0.109)	0.211**	(0.102)	0.026	(0.140)
Ag into—neighbor	−0.113	(0.126)	−0.046	(0.117)	−0.110	(0.168)
Ag info—another farmer	0.234**	(0.116)	0.023	(0.107)	−0.102	(0.170)
Weather info—government	0.284**	(0.142)	0.331**	(0.137)	0.084	(0.198)
Weather info—radio	0.143	(0.097)	0.147*	(0.089)	−0.171	(0.140)
Weather info—television	−0.116	(0.148)	0.131	(0.136)	0.001	(0.197)
Weather info—traditional	0.076	(0.116)	0.006	(0.111)	−0.191	(0.161)
Weather info—neighbor	−0.019	(0.138)	−0.386***	(0.124)	−0.023	(0.194)
Constant	−0.600	(0.379)	−0.929***	(0.338)	−2.407***	(0.503)
ρ_{21}	0.389***	(0.056)				
ρ_{31}	0.073	(0.080)				
ρ_{32}	0.663***	(0.093)				
Observations	1,244		1,244		1,244	

****, **, and * are significant at 1, 5, and 10% respectively.*

happening, or not happening, in Vietnam. Unlike what we find in the household model, the range of individuals that report taking no action to climatic stress is more homogenous across provinces. Taking no action ranged from 32% in Nam Dinh to 42% in An Giang. Most individuals in all provinces already use an autonomous response; however, the adaptation they use varies by location. Reporting a crop change response such as diversifying crops, adjusting the cropping pattern, or leaving land fallow, is the most commonly cited climate change adaptation. Anywhere from 47 to 61% of respondents from each province reported making one of the abovementioned changes to their cropping practices.

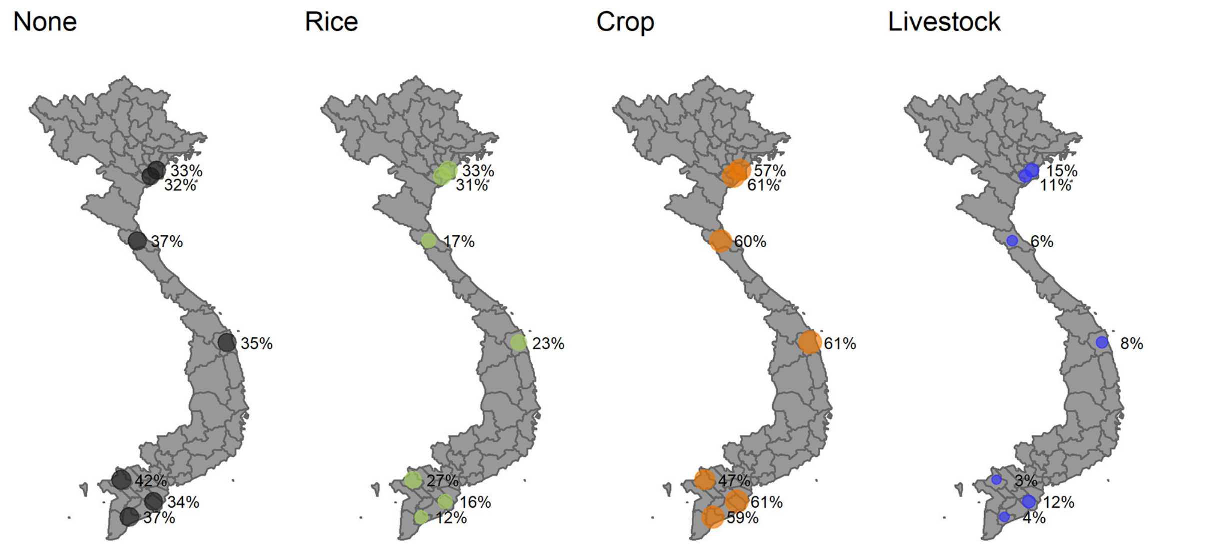

FIGURE 3 | Map showing the percent of respondents practicing agricultural adaptations in each surveyed province.

Responding with a change specific to rice production (i.e., changing rice variety) is the second most commonly cited response behind crop change. However, adopting a new rice variety is the most common response when compared to the individual components of the aggregated crop change response variable. This finding is similar to Trinh et al. (2018), who found changing rice variety was the most popular adaptive practice in their study area. While this is a popular option in our study, there are considerable differences across locations for changing rice varieties. This variation is likely a result of the types of stress present in each of the provinces. The popularity and availability of stress-tolerant rice varieties differ with each of the stresses. The provinces that report changing their rice variety least often are the same provinces that report salinity stress most frequently. While this result may indicate a lack of interest or availability in saline-tolerant varieties at the time of our data collection, a study conducted after our survey by Paik et al. (2020) suggests that salinity-tolerant varieties in the Mekong River Delta are now widely adopted.

Changing from rice to livestock is the least common adaptation selected for all provinces. The rice and crop changes we previously discussed are all short-run adaptations in which inputs to production are varied (Stern, 2007). Livestock is a form of capital (Jarvis, 1974), and capital adjustments are long-run adaptations that are more difficult for individuals to use because of increased uncertainty (Stern, 2007). Individuals from the Red River Delta report livestock investments most commonly, but only 15% of individuals in Thai Binh and 11% of individuals in Nam Dinh report this option. Outside of the Red River Delta, adapting to climate change through livestock is sparsely reported, with all other provinces reporting in the single digits, except for Tra Vinh, where 12% of individuals reported using making a livestock change.

CONCLUSIONS

This article set out to better understand if some climatic stresses or impacts from climatic stress elicited stronger climate change adaptations from individuals. The answer to this question is a resounding yes. At the individual adaptation level, drought, flooding, and to a lesser extent, storms and salinity intrusion, elicited the strongest autonomous adaptations from individuals. The most common autonomous response at the household level is to have a financial adaptation, such as selling assets, borrowing money, or using savings. Households using a financial response may provide an opportunity for microfinance lending in Vietnam as a way to build capacity and reduce vulnerability in households as they adapt to climate change. Autonomous adaptations taken in the private market are generally understood to be efficient. Microfinance is a way for poorer households to access the additional resources necessary to carry out efficient autonomous responses to climate change.

Compared to the household level, sources of climatic stress are less critical for adaptation decisions at the agricultural level. At this level, impacts brought on by climatic stress elicited stronger adaptation responses from individuals than the sources of the stress. Farmers who experienced low yields as a result of stress are more likely to adapt their rice-farming practices through changing the variety of rice that they grow. Our results provide field-level evidence that the sources of stress vary across landscapes in Vietnam. These results show the necessity for location-specific adaptation policies in Vietnam, which have been called for in previous publications.

Furthermore, this study provides policymakers with evidence of which stresses, and where, are already causing autonomous adaptations among individuals and the different responses individuals are using. Equally important as climate change action is climate change inaction. We did not find climate change adaptations resulting from specific stresses, such as sea-level rise and saltwater intrusion. This leaves room for a government response to those stresses where private adaptations are presently absent. All the while, the government can financially support private autonomous adaptations, through channels such as microfinance lending. Of course, autonomous adaptations alone are not enough. Instead, it should be seen as a way to help individuals help themselves in the short run, while other planned adaptations and mitigation options are established as part of a comprehensive climate change policy.

DATA AVAILABILITY STATEMENT

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

ETHICS STATEMENT

Ethical review and approval was not required for the study on human participants in accordance with the local legislation and institutional requirements. Written informed consent for participation was not required for this study in accordance with the national legislation and the institutional requirements. Approval for data collection was granted by all necessary levels of government in Vietnam and verbal consent was obtained by all participants.

AUTHOR CONTRIBUTIONS

All authors contributed to the study conception and design. Material preparation and data collection were performed by VP. Data processing and analysis were performed by JM and JL. The first draft of the manuscript was written by JM and all authors provided revisions to the manuscript.

FUNDING

This research was implemented as part of the CGIAR Research Programs Climate Change, Agriculture, and Food Security (CCAFS), and RICE which are carried out with support from CGIAR Fund Donors and through bilateral funding agreements. For details please visit https://ccafs.cgiar.org/donors. The views expressed in this document cannot be taken to reflect the official opinions of any of these organizations. The study was initiated as part of the Policy Information and Response Platform on Climate Change and Rice in ASEAN and its Member Countries (PIRRCA) Project under CCAFS.

ACKNOWLEDGMENTS

The authors would like to thank the Institute of Policy and Strategy for Agriculture and Rural Development (IPSARD) and the Vietnam National University of Agriculture (VNUA) for assisting in conducting the survey. Lastly, we thank all the households who participated in the survey.

SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fsufs.2021.762650/full#supplementary-material

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Conflict of Interest: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

frontiers in Sustainable Food Systems

ORIGINAL RESEARCH
published: 18 November 2021
doi: 10.3389/fsufs.2021.748300

Adapting to Climate Change Through Conservation Agriculture: A Gendered Analysis of Eastern Zambia

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Specialty section:
This article was submitted to
Climate-Smart Food Systems,
a section of the journal
Frontiers in Sustainable Food Systems

Received: 27 July 2021
Accepted: 27 October 2021
Published: 18 November 2021

Citation:
Umar BB (2021) Adapting to Climate
Change Through Conservation
Agriculture: A Gendered Analysis of
Eastern Zambia.
Front. Sustain. Food Syst. 5:748300.
doi: 10.3389/fsufs.2021.748300

This study explored the use of conservation agriculture (CA) as a climate adaptation strategy among smallholder farmers in Eastern Zambia. Using 761 household interviews and 33 focus group discussions (FGDs) with smallholder farmers from six districts, data was collected on how smallholder farmers in the region experience climate change, what CA practices they had adopted, and benefits and challenges associated with CA practice. Results show that men and women farmers had similar experiences of climate change, namely late onset of a shortened rainy season, intra-seasonal drought and higher temperatures. Farmers' perceptions of gender-mediated effects of climate change had important nuances. The three most cited effects of climate change on women mentioned by women were lower crop yields, outbreaks of armyworms and reduced livestock fodder. The men thought women were most affected by increased hunger, lower crop yields and reduced domestic water sources. According to the women FGDs, men were most affected through reduced crop yields, increases in livestock diseases and increased hunger. The men self-reported reduced crop yields, reduced water for livestock and outbreaks of armyworms. Both men and women saw CA as having climate change adaptation benefits. For the women, men most benefitted from CA through the high moisture holding capacity of basins, higher crop yields and reduced labor requirements through use of oxen ripping. The men most appreciated the high crop yields, improved soil fertility and reduced costs as less fertilizer is used. The women cited the high moisture holding capacity of basins, high crop yields and improved soil fertility as benefits they most commonly derived from CA, while the men thought the women most benefitted from CA through the higher crop yields, improved soil fertility and crop tolerance to droughts. The study concludes that there is room for CA to serve as a climate smart agricultural system for both men and women smallholder farmers in Eastern Zambia. However, this will require addressing important challenges of high weed pressure, high labor demands, and low access to manure, and CA farming implements. The CA package for Zambia should include access to timely climate information and climate informed crop choices.

Keywords: climate smart agriculture (CSA), minimum tillage (MT), gender role, ripping, smallholder farmers, basins

INTRODUCTION

The Inter-Governmental Panel on Climate Change (IPCC)'s Fourth Assessment Report recognized that gender roles and relations shape vulnerability and people's capacity to adapt to climate change (IPCC, 2007). The report noted that rural women in developing countries were one of the most vulnerable groups. Extensive empirical literature has shown that female-headed farming households in Sub-Saharan Africa produce up to 40% less than male-headed households (Udry et al., 1995; Goldstein and Udry, 2008; Doss et al., 2011; FAO, 2011; Kilic et al., 2015; Slavchevska, 2015; Gebre et al., 2021) and earn less income (Zulu-Mbata and Chapoto, 2016; Teklewold et al., 2019). This is attributed to systematic and persistent differentials in access to and use of agricultural inputs; tenure security and related investments in land; market and credit access; and informal institutional constraints (Doss and Morris, 2000; Alene et al., 2008; Johnson et al., 2015; Kilic et al., 2015). Women's less access to productive agricultural resources makes them more vulnerable to climate change/variability effects. Women are likely to be more negatively affected by climate change than men are because they have fewer resources with which to adapt to it (Thomas et al., 2007; Goh, 2012; Antwi-Agyei et al., 2013). Women's greater vulnerability compared with men also arises from social and cultural norms (Terry, 2009; Codjoe et al., 2012; Goh, 2012). For instance, gendered divisions of labor, physical mobility, and participation in decision making at household and community levels are socio-cultural norms that mediate women's vulnerability to climate change effects.

Women's roles entail that their perceptions of climate risk may be different from those of the men in important ways (Lambrou and Nelson, 2010). Men and women have different social positions and obligations, which means they have different opportunities to incorporate climate change adaptation strategies into their lives (Seasoned Development Solutions, 2021). Parks et al. (2015) found that men and women had different access to assets, gender roles, and soil perceptions that could have implications for whether farmers adopt conservation agriculture in the Philippines. In their study in Andhra Pradesh, India, Lambrou and Nelson (2010) found that men were significantly more likely than women to report there was less fodder and that boreholes and ponds had dried up while women were significantly more likely than men to report that health was affected.

In targeting smallholder-based agricultural growth, national development plans across sub-Saharan Africa have emphasized the reduction of gender differences in agricultural productivity (Kilic et al., 2015; Johnson et al., 2018; AU/NEPAD, 2019). With the reported increased frequency and intensity of extreme climatic change events in sub Saharan Africa (Thierfelder and Wall, 2010; Asafu-Adjaye, 2014; Stevens and Madani, 2016; Government of the Republic of Zambia, 2017; Zougmoré et al., 2018), most agricultural interventionists have endeavored to promote adaptation to and mitigation of climate change effects by including climate resilient agricultural technologies to their development packages (Government of the Republic of Zambia, 2016; AU/NEPAD, 2019; Michler et al., 2019; Teklewold et al., 2019; Diko et al., 2021). This has resulted in the promotion of climate smart agriculture among smallholder farming communities in several countries across the region (Andrieu et al., 2017; Zougmoré et al., 2018). The Food and Agricultural Organization (FAO) conceptualizes climate-smart agriculture as an approach that helps to guide actions needed to transform and re-orient agricultural systems to effectively support development and ensure food security in a changing climate (FAO, 2013). FAO elaborates that climate-smart agriculture aims to tackle three main objectives: (i) sustainably increasing agricultural productivity and incomes; (ii) adapting and building resilience to climate change; and (iii) reducing and/or removing greenhouse gas emissions, where possible.

In Zambia, attempts to transform and re-orient conventional agricultural systems to ensure food security amidst a changing climate have been made through the promotion of conservation agriculture (Haggblade and Tembo, 2003; Nyanga, 2012). Conservation Agriculture (CA) is any agricultural system based on three main principles: minimal soil disturbance, permanent soil cover and crop rotations. The principles are lauded to be universally applicable in all agricultural landscapes and cropping systems and adaptable to local conditions and needs (FAO, 2016). Common CA practices promoted in Zambia are dry-season preparation of a precise grid of basins using hand hoes; dry-season ripping using oxen or tractor; retention of crop residues within field; spot application of inputs such as seeds, fertilizers, lime and manure; and crop rotations that include annual legumes (Umar et al., 2011).

CA is hypothesized to mitigate climate change (Hobbs and Govaerts, 2010; Farnworth et al., 2016; Gonzalez-Sanchez et al., 2018; O'Dell et al., 2020). It is reportedly effective in mitigating the negative impacts of deviations in rainfall (Thierfelder and Wall, 2010; Umar and Nyanga, 2011; Michler et al., 2019). Using nationally representative data, Zulu-Mbata and Chapoto (2016) found that male headed households tended to practice ripping (animal draft powered and mechanized tillage) more than female headed households, while females in female headed households tended to practice crop rotation more than farmers in other household dynamics.

Integrating CA practices inevitably affects on-farm gender relations, notably resource allocation as well as having an impact upon the ability of women and men to realize their gender interests (Farnworth et al., 2016). Empirical studies have shown that shifting of labor from tasks performed by men to those performed mainly by women when CA is adopted lead to increases in women's labor burdens (Baudron et al., 2009; Giller et al., 2009; Nyanga et al., 2012). Although some CA proponents present basins as being apt for women farmers, the technology was not tailor made for women. Its use by men and women farmers results in differentiated outcomes. Women found the *Chaka* hoe-designed for use in making basins-to be very heavy to use and manual weeding of basis laborious (Andersson et al., 2011; Rusinamhodzi, 2015). Generally, agricultural technology adoption outcomes depend on local context (socio-cultural, policy, and biophysical environment). As noted by Gebre et al. (2019) agricultural technology adoption in relation to gender is context-specific and common conclusions are challenging to reach. In promoting CA as a "one size fits all" technology package without much attention for existing farming practices and the suitability of the promoted technologies within the socio-economic context in which they are to be adopted (Baudron et al., 2012), CA protagonists risk low adoption levels and sub-optimal outcomes. CA interventions in Southern Africa have resulted in low adoption (Brown et al., 2017; Bouwman et al., 2021), disadoption of CA post project (Arslan et al., 2014; Chinseu et al., 2019; Habanyati et al., 2020) and conflicts between some CA and conventional agriculture practices (Giller et al., 2009; Thierfelder et al., 2012; Valbuena et al., 2012). Thus, micro and meso level studies are important to inform planned agricultural interventions (see Sumner et al., 2017 for the importance of understanding gendered practices and perspectives in CA technology promotions). After a systematic review of sustainable intensification, Himmelstein et al. (2016) advised that methodologies must depend upon adaptations of several development techniques for different types of communities. For this reason, the World Bank, in conjunction with TerrAfrica commissioned a study to build evidence on gender concerns in the context of projects and programmes focused on sustainable land management and climate change in Eastern Zambia. Previous interventions and studies in the region focused on the promotion of agricultural technologies without due consideration to the central role of gender roles and gender relations in mediating outcomes among the smallholder farming communities. This study aims to narrow this knowledge gap and contribute to theory on gender responsive analysis of conservation agriculture and sustainable land management. It provides a methodological roadmap for development interventionists by highlighting the importance of socio-cultural and biophysical context in the outcomes of agricultural development projects.

Eastern Zambia was purposively selected because of its rich history with sustainable land management interventions by an array of development actors. Agricultural development interventions have been focused on the region because it is an agricultural region with untapped potential. Eastern province had 349,980 agricultural households during the 2017/2018 agricultural season. Of these, 77.7% were male headed while 22.3% were female headed. Almost all the households (97.7 and 97.2% for male and female-headed households respectively) produced crops. Livestock was raised by 77.9 and 64.7% of the male headed and female-headed households respectively (Ministry of Livestock and Fisheries, 2019). About 5% of farming households had fully adopted CA while 7% were partial adopters in 2014 (Zulu-Mbata and Chapoto, 2016). In its Seven National Development Plan (2017 to 2021), the Government of the Republic of Zambia committed to ensure equitable distribution of national resources between women and men, girls and boys for meaningful impact in the medium and long-term on poverty reduction among women and girls.

This sub component of the study aimed to examine the practice and benefits of CA in Eastern province through a gender lens. It was guided by four research questions; (i) to what extent do experiences of climate change differ between men and women smallholder farmers in the Eastern province? (ii) how do men and women smallholder farmers practice CA in Eastern Province (iii) what benefits do men and women smallholder farmers derive from CA, and (iv) What challenges do men and women smallholder farmers face in the of practice of CA. These research questions were based on the premise that there are important differences in gender roles which mediate how men and women smallholder farmers practice and the conditions under which they practice CA in Eastern province. Local gender norms and practices mediate the benefits women and men accrue from CA. This study contributes to understanding how men and women farmers in Eastern province have benefited from CA as a climate smart agricultural system; and the challenges they have faced in their practice of CA. This information is useful to interventionists with agricultural development programmes in the region. The study also contributes to scholarship on CSA in Sub Saharan Africa. The rest of the article is organized as follows; the next section details the research methodology and explains how the primary data for the study was collected from a range of sources. This is followed by a combined results and discussion section, after which the study is concluded.

METHODOLOGY

Study Area and Context

The study was conducted in the rural parts of six out of 11 districts of the Eastern Province in Zambia (**Figure 1**). The Eastern Province experiences seasonal rainfall of between 800 and 1000 mm and a crop-growing period of 100–140 days. This is suitable for production of a range of annual crops and raising of livestock. Like other regions of Zambia, the Eastern Province is characterized by three seasons, warm and wet (from November to May), cold and dry (June to august) and hot and dry (September to November). Zambia has a uni-modal rainy season, around which smallholder agricultural activities are organized. Pre-tillage land preparation activities usually begin in October. After the first rains and a softening of the soils, tillage begins in late October/early November. Planting begins as soon as the first effective rains are recorded, from around mid-November and goes on until December. Each field is weeded between 1 and 3 times, depending on the crop planted and the availability of labor. Harvesting of fresh maize starts as early as March while the main harvest period is only after the rainy season has ended and the maize crop has dried. Between May and June, all the crops are harvested and readied for the marketing season, which lasts until October when the cycle repeats.

Majority of the rural dwellers in the province are engaged in rain-fed agricultural production while some do irrigated vegetable production during the dry season. The main crops grown are maize (Zea Mays), groundnuts (Arachis hypogaea), cotton (Gossypium hirsutum), tobacco (Nicotiana tabacum), soya beans (Glycine max), sweet potatoes (Ipomoea batatas), cowpeas (Vigna unguiculata), millet (Panicum miliaceum), sorghum (Sorghum bicolor), rice (Oryza sativa), cassava (Manihot esculenta), common beans (Phaseolus vulgaris) and sunflower (Helianthus annuus). Common livestock reared are cattle, goats, and pigs. Almost every household has free-range chickens, and less commonly ducks, guinea fowls, and geese.

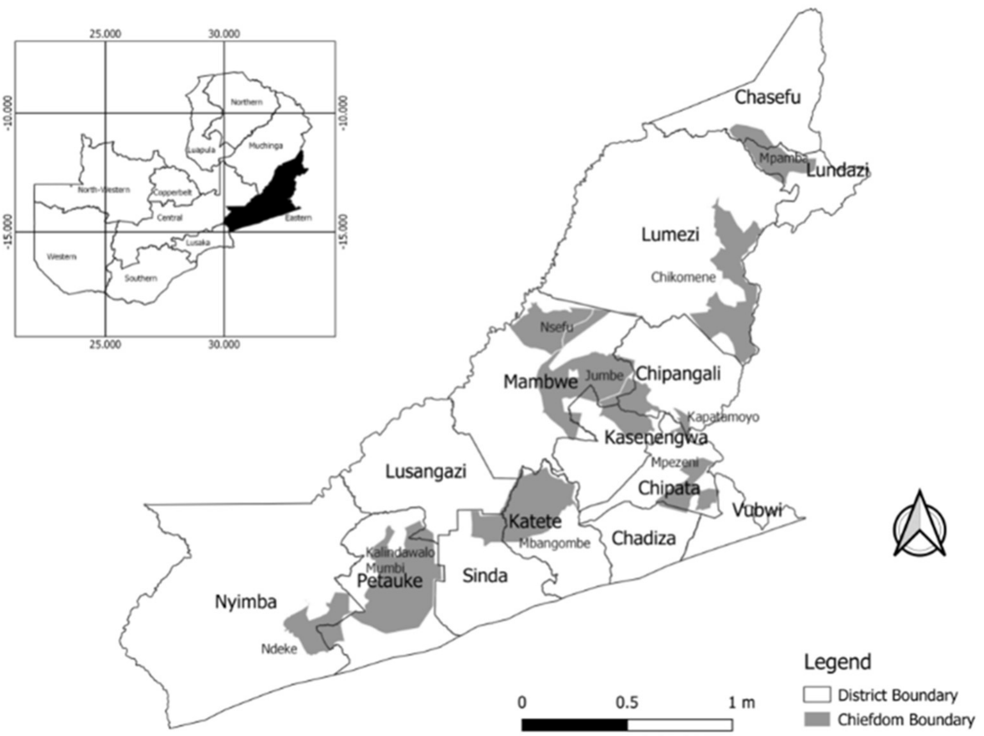

FIGURE 1 | Map of Eastern Zambia showing study districts and study sites.

Research Strategy and Data Collection Methods

An exploratory sequential mixed method research design was used (Bryman, 2012). An initial phase of qualitative data collection using focus group discussions (FGDs) and unstructured interviews with key informants was followed by a quantitative cross sectional household survey component. The qualitative phase of the study was essential for the researchers to understand the local socio-cultural, political and institutional context. The insights gained from the qualitative part of the study informed the issues to examine during the household survey. The FGDs and key informant interviews further provided insights into structural factors and power relations that were not obvious from the household survey.

Data was collected from 33 focus group discussions and 761 households in 11 chiefdoms namely Chikomeni, Chikube, Jumbe, Kalindawalo, Kapatamoyo, Mban'gombe, Mpamba, Mpezeni, Mumbi, Ndake and Nsefu. Two stage probability sampling was done to select survey respondents. The first stage involved the purposive selection of the districts and chiefdoms to cover different tribes, areas most dependent on agriculture and forest resources for livelihoods and where sustainable land management projects have been implemented. The second stage involved a random selection of proportionate number of households using village registers. The focus group discussants were initially separated into single gender groups, men and women. The initial separation into single gender groups was important to minimize any potential influence of unequal gender relations. The groups were combined in a plenary session and asked to present summaries of their group deliberations. Gender was conceptualized as the socially constructed roles and behaviors that a society typically associates with males and females.

The FGDs were conducted in the local dialects of the province namely Tumbuka, Ngoni, Nsenga, Chewa and Kunda. Members of the research team expertly facilitated the discussion, observed the proceedings and took notes. The facilitators alternated which group shared its results first. Both facilitators and observers paid attention to the verbal and non-verbal reactions of the women to the men's answers, and *vice versa*. Informed consent was obtained and permission to record the discussions using digital recorders was sought and granted for all the sessions. Respondents for the household survey were selected from gender-disaggregated lists of previous sustainable land management project participants in each Chiefdom. Key informant interviews were conducted with experts from non-governmental organizations and government agencies operating in the agricultural sector in the study sites.

Data Analysis

The recordings of the focus group discussions were transcribed into English. They were then analyzed using thematic analysis method with the aid of the qualitative analysis software QDA Miner 4.0 (Provalis Research, 2011). Four themes were selected based on the research objectives as follows; experiences of climate change, CA practices, benefits of CA, and Challenges of CA. The quantitative data was analyzed using MINITAB

18 (MINITAB, 2017) to test for differences in household sizes and age between male and female-headed households using Two-Independent sample T-Test; to test for differences in household size among the six study districts, livestock and implement ownership using ANOVA; differences in proportions between male and female respondents using two-sample Z-proportions test. All the analyses were conducted at 5% level of significance.

RESULTS AND DISCUSSION

Social–Demographic Characteristics of Study Respondents

Of the 761 households interviewed during the survey, about 79% were male-headed with the remaining 21% of the sample representing female-headed households (**Table 1**).

TABLE 1 | Distribution of survey respondents by gender, eastern Zambia.

District	Gender	
	Female-headed	Male-headed
Chipata	41 (5.4%)*	126 (16.6%)
Katete	7 (0.9%)	36 (4.7%)
Lundazi	20 (2.6%)	90 (11.8%)
Mambwe	34 (4.5%)	73 (9.6%)
Nyimba	29 (3.8%)	161 (21.2%)
Petauke	31 (4.5%)	113 (14.8%)
Total	162 (21.3%)	599 (78.7%)

Number in parenthesis indicates percentage of total sample size.

Overall, a significant proportion of the respondents had attained primary level of education (**Figure 2**). The results show that men were generally more educated than women were.

Household size was used as a crude proxy variable for labor availability. On average, each household had a total of 6 members. In addition, there were ∼3 males and 3 females in each household. However, there was a statistically significant difference in the household size between female-headed households with an average of 5 individuals and male-headed households with an average of 6 ($T = -4.52$; $p = 0.001$). The average household size also differed statistically among districts particularly Lundazi differed from Petauke, and Nyimba ($F = 2.917$; $p = 0.013$). Petauke district had 7 members on average while Nyimba had 6 members and Lundazi district had 5 members. Most of the respondents were married (77.5%). The average age of men were significantly higher (44.9) than that of women (40.8), ($T = 5.36$; $p = 0.001$). More results on social economic characteristics are presented as supplementary material (**Supplementary Table 1**). Married households, synonymous with large families and associated labor availability are more likely to adopt new practices, especially those that are more time consuming e.g., basins under CA (FAO and UNDP, 2020). Smaller household sizes for female-headed households meant lower access to labor, compared to male-headed households.

Climate Change Experiences of Men and Women Farmers

Survey results showed that almost all respondents (98%) were familiar with the concept of climate change. Late on set of the rainy season and a shortened rainy season were the most reported experiences of climate change by both male and female respondents (**Figure 3**).

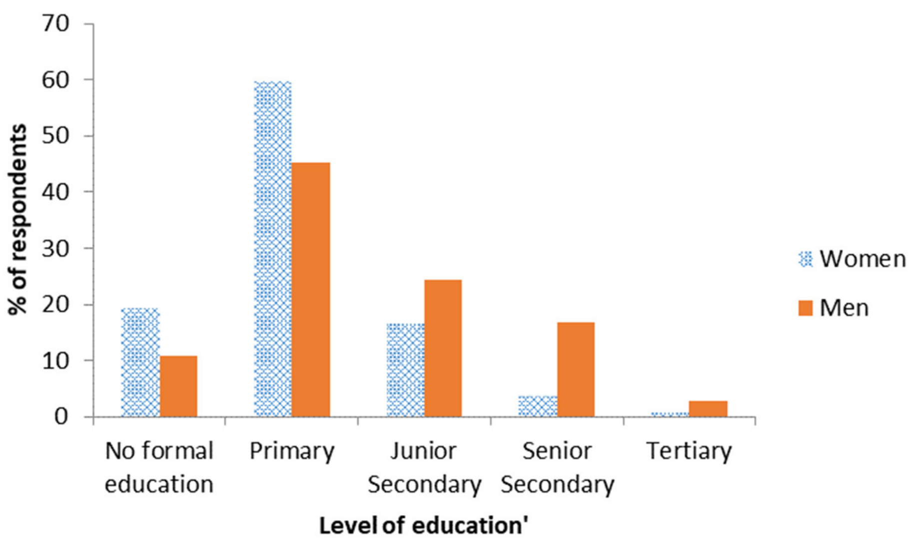

FIGURE 2 | Educational attainment of household heads and their spouses.

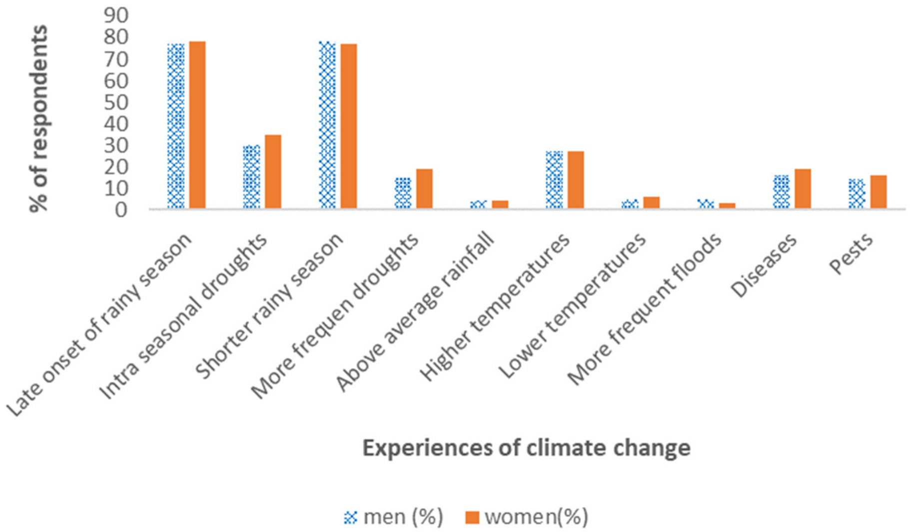

FIGURE 3 | Survey results on experiences of climate change by men and women farmers.

Men and women's focus group discussants had similar perceptions of how climate had changed in Eastern Province.

There was a consensus across all the districts and between men and women on climate change manifesting through late onset of the rainy season and a shortened rainy season. Focus group discussants typically referred to early onset of rains in the past by referring to important days such as Zambia's independence day, Christmas and local annual traditional ceremonies. For instance, one woman discussant from Nyimba said this, "*When we were young, it used to rain on independence day, or even before. Even our parents told us that by independence day holiday, it would have started raining. But nowadays, by the time we are celebrating Christmas, there are no rains.*" An illustrative quote from the men's FGDs in Nyimba is the following, "*before we used to get good rains. It would rain over a longer period. It would rain just after we came back from the Tubimba ceremony held in September.*" In a survey of 86 men and 86 women smallholder legume farmers in Chipata, eastern Zambia Mphande (2021) reported that both men and women similarly perceived that climate change in Chipata manifested through shorter rainy season, late start of rainy season, intra–seasonal droughts and heavy downpours. The confirmation of similarities in perceptions of climate change between men and women provides a background to the results on gendered perspectives on effects of climate change, that is, any differences in effects of climate change between men and women derive from mediating factors, including gender.

Survey results show that almost two-thirds (65.4%) of the respondents thought that there were no differences between how men and women were affected by climate change, while 34.6% perceived differences. Results from the men and women's FGDs show both differences and similarities in their perceptions of effects of climate change and women (**Figure 4**). All the women's FGDs observed that climate change had resulted in women experiencing lower crop yields. Half of the women's FDGs mentioned outbreaks of armyworms (*Spodoptera frugiperda*), as having exacerbated low crop yields. An overall reduction in average rainfall (due to a shorter rainy season) was noted to have led to less water in streams and subsequently less fodder and water for livestock, and women having to walk longer distances to get water from the few water sources that were still perennial. Due to streams drying up, grasses also dry up, resulting in fodder and water shortages for livestock.

The women discussants explained that due to poor rains, they get very poor maize and groundnut yields. Pests attack the maize further reducing the yields. Consequently, households experience hunger and reduced crop incomes.

The women discussants also noted a shift in the maize varieties they planted. In the words of one woman discussant from Mambwe district, "*Today we cannot plant local maize. If you do you get nothing. Local maize used to do well when rains started early and ended late. Now we plant early maturing varieties from the shops*" Replanting of crops has reportedly become increasingly common. The women discussants noted that rains nowadays "disappear" after they plant. The seeds fail to germinate, forcing the farmers to replant. Sometimes they fail to replant. "*We cannot replant as we have no money and it is too late in the season*" narrated one women discussant from Chipata. Another women from the same FGD mentioned this, "*due to climate change, we get very low yields. We did not apply fertilizer as we kept waiting for the rains. Now it is too late to apply it. Our crops are stunted at knee height. It is only Jesus who knows how we shall survive.*"

A women from Mambwe narrated the following, "we *had to plant rice in March because the rains disappeared in January when we should have planted the rice*" Similar narrations were noted from women FDGs in Chadiza.

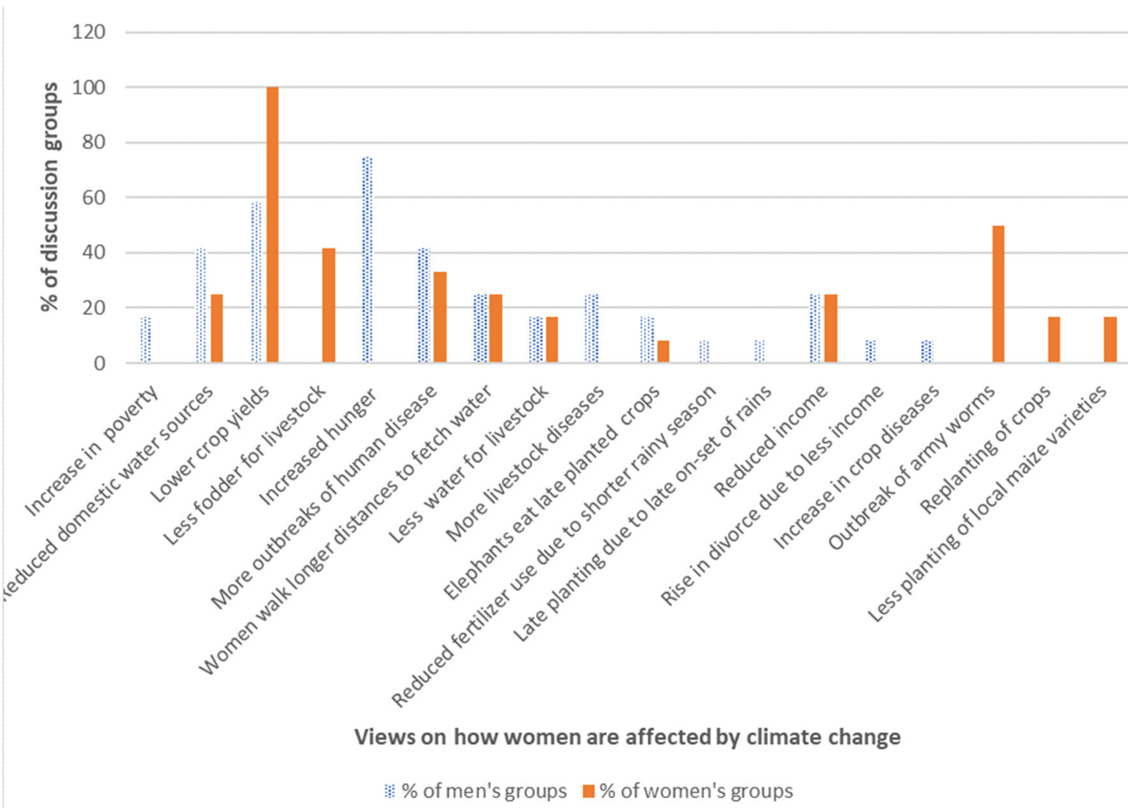

FIGURE 4 | FGDs' views on how climate change affects women.

"*maize does not germinate as there are no rains so we are forced to replant. We do not have any surplus maize to sell. Women suffer more because a woman has to look for food for the household. The men use the money on beer but expect to find food. We still give them food.*"

The women's FGDs from Mambwe district narrated increased wildlife conflicts as having resulted from changes in the local climate. "*Due to late planting, our crops are still in the field in March, so elephants eat them. Before, we would plant early and harvest by March.*" The women contended that they were more negatively affected by climate change for several reasons. They expressed views such as the following:

"*Women suffer more due to climate change as they look after children.*"

"*There are more diseases when there are droughts so women suffer more as they have to take children to hospitals. Men just drink.*"

"*Water is scarce. We have to move longer distances to find water.*"

Men thought that increased hunger, lower crop yields, reduced domestic water sources, reduced agricultural income and more livestock disease was how climate change most commonly affects women (**Figure 4**). The men elaborated that women suffer when elephants eat late-planted crops. Crops are planted later than was previously the case due to shifts in the start of the rainy season. Women use less fertilizer on late-planted crops because they are averse to using fertilizer when they are not sure how the rainy season will perform. The reduction in fertilizer amendment further lowers crop yields. Such crops are also easily attacked by disease, they explained. Men listed 14 effects of climate change on them, out of which women only mentioned half. Women mentioned 11 effects of climate change on women, out of which seven were similar to those mentioned by men, and four were unique to the women. Although most of the perceptions between men and women related to gender roles, some were further mediated by location and bio-physical characteristics e.g., those in Mambwe District, a hot valley area where the farmers interviewed lived in close proximity to a national park and human wildlife conflicts were pervasive. Reduced crop yields and increased hunger were mentioned for both genders. Smallholder farmers experience low agricultural productivity because of several factors, including low soil fertility due to soil management practices that focus on mineral fertilizer amendments at the expense of holistic soil health; low access to high quality seed, and labor bottlenecks at critical periods of the agricultural season.

Women FGDs thought that reduced crop yields, reduced water for livestock, outbreaks of armyworms, increased pesticide use on crops and increased livestock mortalities where what men commonly faced due to climate change (**Figure 5**). The following quote illustrates the views of women discussants

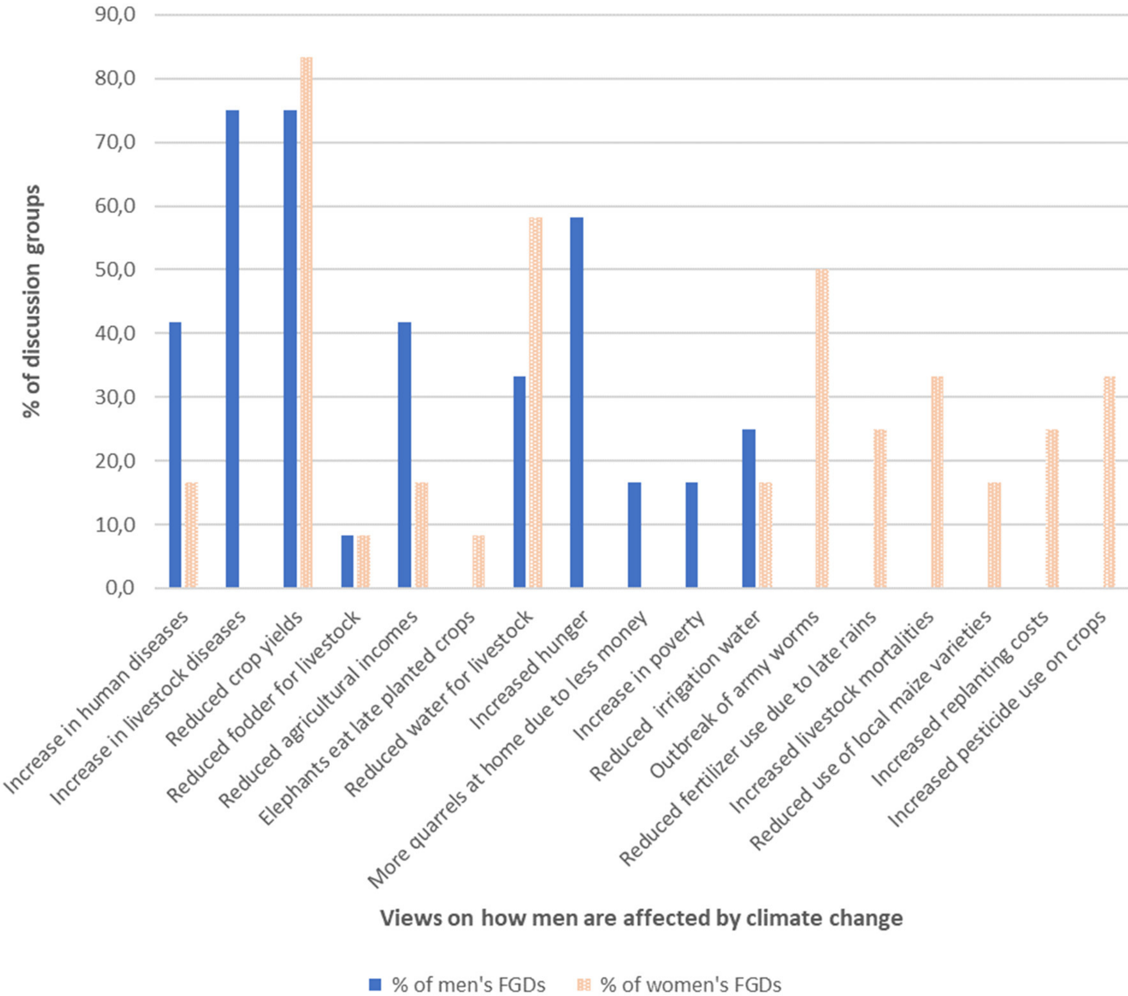

FIGURE 5 | FGDs' views on how climate change affects men.

in Chipata, "*Men are household heads so they have to find money for households. If yields are poor, it falls on the man to find alternative sources of income*. Women FGDs in Mambwe buttressed the human wildlife conflict effect similarly affecting the men as follows

Due to late planting, the crops are still in the filed in march, so elephants eat them. In the past, the crops would have been planted early and harvested by March. So, it falls on the men to find money to buy food for the family. Women FGDs in Chadiza alluded to livestock husbandry challenges that men face due to climate change. "*Lundazi River dries up. The men go looking for water, sometimes in muddy areas, resulting in the smaller livestock being left behind to die stuck in the mud, unbeknownst to the shepherds, who only realize this when they return home.*"

For the men's FGDs, the most commonly cited effects of climate change on men were increase in livestock diseases, reduced crop yields, increased hunger, reduced agricultural income and increase in human diseases (**Figure 5**). In the words of one male discussant, "*due to climate change, poverty has increased. Since we are farmers, climate change affects our yields. They are lower. We earn less*" Some of the men's FGDs argued that the men carry a heavier burden due to climate change because they have to find transport money when household members become ill and to look for money to buy food. Several of the men's FGDs further noted that since livestock diseases increase during droughts, men spend extra time and money on livestock husbandry. Men also reportedly spend more time on transporting water for irrigated vegetable gardening and for livestock. However, when it comes to household chores, the men acknowledged that women ended up with more housework and responsibilities during droughts.

The men discussants explained that during periods of drought–which have become increasingly common–there are shortages of water as most streams dry up. All the livestock in the chiefdom is herded to the few remaining perennial water points. These water points are also frequented by wild animals and humans. This increased use of perennial water points result in contamination of water, and consequently livestock and human

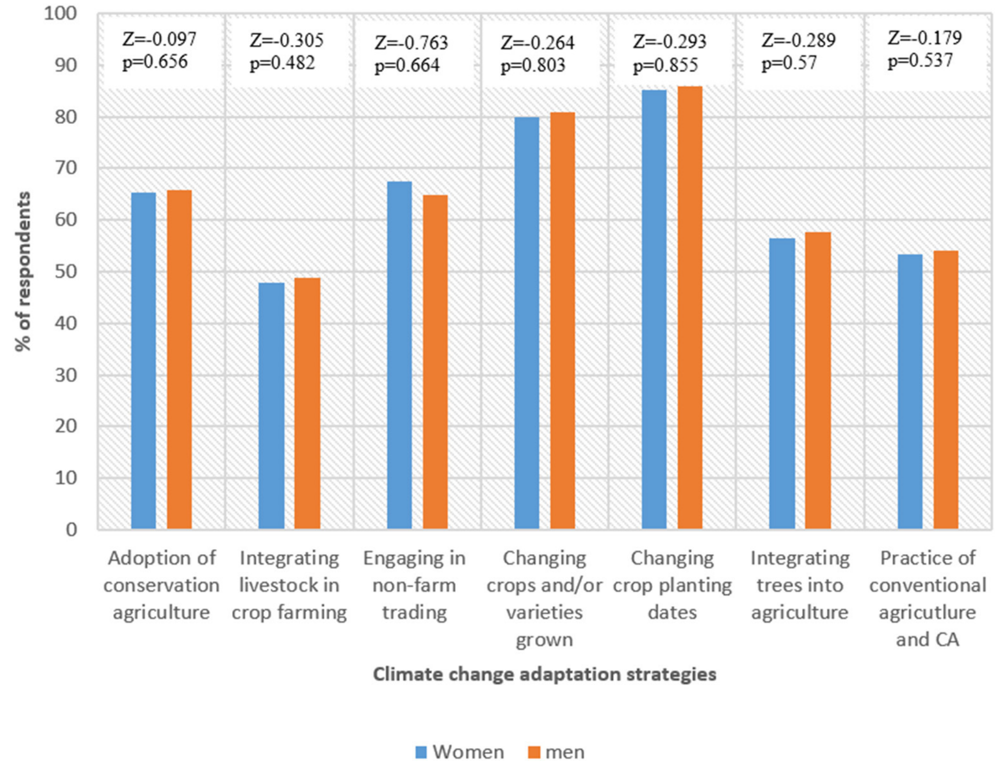

FIGURE 6 | Awareness of climate change adaptation strategies by men and women respondents.

disease. Livestock is very susceptible to diseases during drought periods due to poor nutrition (resulting from scarce and poor quality pasture). The shortage of water also extends to vegetable gardening, which is dominated by men. The men have to ferry irrigation water from much farther and have to deal with increased pest infestations of the vegetables.

The men's FGDs also mentioned that reduced crop and the concomitant reduction in household food security as some of the main effects of climate change. "*climate change has brought poverty. We experience poor yields due to climate change so we do not make money. We suffer. We experience hunger and poverty,*" one male discussant lamented. The men FGDs explained that their other sources of income were appropriation and sale of forest resources. During periods of drought, non–timber forest resources are in short supply. This further reduces their income earning opportunities. The men observed that this situation results in "*increased poverty and quarrels at home. We quarrel over money for food, school*[1] *and hospital bills.*" Essentially, the experience of both women and men was that they incur more costs while earning reduced incomes during drought periods. Men alluded to responsibilities that fall on them by virtue of them being perceived as uncontested household heads. These responsibilities include raising cash incomes when there is need to procure goods and services; irrigation of vegetable gardens and spraying of herbicides.

Out of 13 responses on how men were affected, seven were unique responses from the women. Out of the ten given by men, three were unique. Effects of climate change highlighted by both men and women pertained to both crop and livestock farming, an indicator of the dominance of mixed crop-livestock farming in the province. Dealing with livestock mortalities was limited to men, although both men and women were acknowledged to experience high incidences of livestock disease. Women bemoaned their inability to replant crops after intra-seasonal droughts yet noted that men incurred higher costs doing this, an indicator of men's better access to financial capital.

In light of the various effects of climate change on agricultural activities highlighted during the FGDs, the survey investigated awareness of agricultural related climate change adaptation strategies among male and female respondents. The results are presented in **Figure 6**. There were no significant differences in female vs. male respondents' awareness of climate change adaptation strategies.

CA was seen as an important adaptation measure. Results show that 67 and 67.5% of female and male respondents respectively observed that men and women farmers adopted CA because of climate change. Arslan et al. (2014) found rainfall variability to be a strong determinant of CA adoption as an adaptation strategy among smallholder farmers in Zambia. The

[1]Due to the long distances between villages and secondary schools, most pupils are either in boarding school or rent houses close to their schools. Their parents raise their school and boarding fees through the sale of crops, livestock and forest products.

TABLE 2 | Conservation agricultural practices used by men and women in Eastern, Zambia.

Conservation agriculture practice	Percentage of respondents		Test statistic
	Men ($n = 307$)	Women ($n = 440$)	
Basins	39.8	43.4	$Z = 1.00$, $p = 0.419$
Ripping	31.1	33.2	$Z = 0.644$, $p = 0.323$
Leguminous crop rotation	70.7	78.1	$Z = 2.332$, $p = 0.751$
Crop residue retention	61.6	68.2	$Z = 1.872$, $p = 0.655$
Spot input application	38.5	43.6	$Z = 1.419$, $p = 0.415$
Dry season land preparation	50.3	56.4	$Z = 1.673$, $p = 0.538$
Timely planting	54.5	60.8	$Z = 1.776$, $p = 0.582$

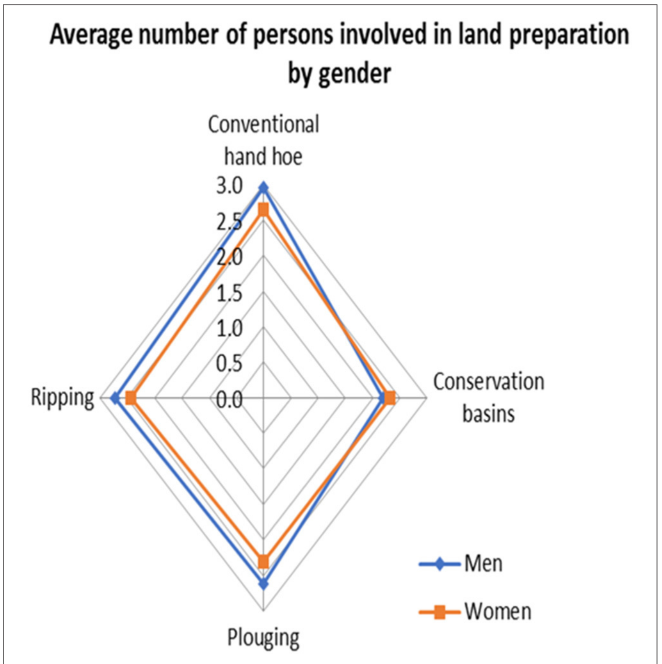

FIGURE 7 | Participation in tillage activities by men and women.

rest of this article presents and discusses results on the practice of CA. It focuses on climate related benefits of CA and discusses to what extent the agricultural system functions as an adaptation strategy to climate change as experienced by men and women farmers in the Eastern Province of Zambia.

CA Practices Employed by Men and Women Farmers

Survey results showed that men and women employed seven different CA practices to varying extents and there were no statistically significant differences in the use of the CA practices by men and women (**Table 2**).

A large proportion of the male farmers engaged in crop rotations, crop residue retention and timely planting. A similar pattern was observed for the female-headed households. Crop rotation has been part of conventional agricultural practice for a long time. Therefore, CA farmers find it easy to include it as part of their shift to CA because it is a practice they are familiar with and its benefits accrue in the short term, unlike agroforestry. Noteworthy were the findings that only around 39 and 44% of the male headed and female households respectively precisely applied their inputs into planting stations and that only a third ripped their fields and about 40% made basins. This suggests that CA tillage methods are still not as common as the conventional methods. Spot input application-the prescribed technique for applying inputs such as seed, fertilizer and manure under CA systems was used by more or less all the respondents that used basin tillage system. On average, more men in terms of average numbers were involved in the tillage activities with respect to plowing, ripping and conventional hand hoeing while women were more involved in providing labor for basin making (**Figure 7**).

Survey results further show that women invested more days (11.7) on average using conventional hand hoeing when compared to men (10.2). However, men allocated more labor days (5.6) to oxen-plowing compared to 3.9 days for women. Thus, women were more involved in labor-intensive tillage activities than the men were. During focus group discussions with men and women drawn from Chipata, the women contended that they did more work, more so because other than the many agricultural tasks they performed, they also fulfilled their reproductive roles. The women did household chores before and after undertaking agricultural tasks. Both men and women were involved in tillage, planting of crops, hand-hoe weeding and harvesting. Spraying of herbicides was mainly done by men. Men and women generally produced the same crops except for tobacco and cotton. One-woman discussant elaborated that, "*men focus on tobacco and cotton. Tobacco production is too demanding on labor. One needs to make a barn, and dry the tobacco. Cotton spraying is a very hard job too, and is usually done by men.*"

The women focus group discussants in Chipata reported being involved in the rearing of goats, pigs and chickens, but not cattle. Sentiments such as "*The men focus on cattle. Cattle requires men*" and "*only men rear cattle. They can afford to. Women cannot manage cattle*" were expressed by some women discussants. The Chipata men's focus group discussants argued that men and women worked equally hard in the field.

In Mambwe, both men and women focus group discussants agreed that they produced the same rain-fed crops but the men engaged in irrigated vegetable production as well. Both genders agreed that they reared the same types of livestock although the women were more involved in the day to day management of chickens while the men focused on the husbandry of large livestock. The women focus group discussants contended that they did more agricultural work than the men and this was because they worried about their children. They echoed statements such as the following;

"*We are the ones to look for food so we have small fields of food legumes. We maintain these fields ourselves,*"

"*We go to the field together, come back together. The man just sits in his chair while I cook, prepare water for his bath,*" "*We go into the forests, we go to the fields, we cook, we look after children … while the man just sits. In the night he says 'move closer,' more work. When do we rest*?"

"*In the olden days, men used to go to the fields early, but nowadays men and women go at the same time,*"

"*A few of the men help, mostly those that do not take alcohol. Alcohol is a problem. When a man drinks, he makes noise at home and refuses to work in the field the following day.*"

These statements seem to suggest that women perceive themselves to work more than the men because of their triple roles, which increase their average work burden on any given day.

In Lundazi, men and women both observed that they had different agricultural roles, and the extent to which the different genders were involved was partly influenced by tillage methods, farming implements and other technologies used. Both men and women were involved in pre-tillage land preparation which entailed the cutting of branches and uprooting of herbaceous plants. Axes and hand hoes were used by both genders albeit the women used smaller ones. When hand-hoes were employed for tillage, the men reportedly did as much work as the women. Conversely, the men almost exclusively tilled the land when the tillage method used was oxen plowing. The discussants further observed that planting of crops was mostly done by women. Hand–hoe weeding was performed by both men and women. However, when herbicides were available for weed management, the task fell on the men although, "*a few women spray herbicides too.*" Both men and women focus group discussants considered crop harvesting to be women's work. One women discussant noted that "*a few of the men get involved but this is rare*" while another narrated that, "*the men go to drink while the women harvest the crops.*" Some types of livestock were reared by men and women in Lundazi, including cattle, although the men were noted to have a dominance in cattle husbandry.

Similar to their Mambwe counterparts, Lundazi women contended that they performed more work than the men overall because they have non-agricultural work which increases the drudgery they experience when they undertake agricultural activities. Chipata men and women expressed views similar to the Lundazi ones on labor allocation for rain-fed crop production. The Chipata women reiterated that, "*only women without husbands spray herbicides. Some widowed women ask their adult male children to spray herbicides for them.*" The women focus group discussants noted that only men engage in irrigated vegetable production. This was reportedly because, "*gardens require a lot of labor.*" Chipata men and women reportedly produce the same rain-fed crops except for tobacco, which is considered men's crop. Women discussants insisted that they reared the same types of livestock as the men. "*Yes, even us women have cattle. We own cattle as women, and also engage in its husbandry.*" During the joint FGDs, a consensus was reached that when it comes to agricultural activities, men worked more than women as in addition to producing the same rain-fed crops as the women, they also engaged in irrigated vegetable production.

Petauke men and women disagreed on who performed more agricultural work. The men argued that they engaged in pre tillage land preparation, oxen plowing and oxen ripping, basin making and spraying of herbicides, as well as crop marketing. However, the women contended that men used animal draft power to plow and weed, while the women depended upon manual and labor intensive hand hoes for tillage and weeding. The women insisted that nowadays there were women that actively participated in oxen plowing and herbicide spraying but noted that this was commonly women without husbands.

Survey results showed that most farming households engaged in manual weeding (90%). The number of adults involved in manual weeding are indicated in **Figure 8**.

There was greater involvement of women in weeding conducted under conventional and CA system compared to men. A similar pattern was also apparent for the average number of days allocated to weeding for all the tillage types considered. Both male-and female-headed households hired casual labor for tillage, planting, weeding and harvesting activities. Hired labor was mostly needed for tillage and weeding, with 24% of the male-headed households indicating hiring labor for tillage compared to 7.3% of the female-headed households. About 16% of the female-headed households enlisted the assistance of local community members for weeding when compared with 19% of males. The lower percentage of female-headed households hiring labor due to their lower capability to pay for hired labor. The current analysis of CA practices by men and women smallholder farmers reveals that norms around gender roles are carried over into CA practice. Women have more work under CA than men do because they dominate the manual labor-intensive tasks and have time-consuming reproductive roles. Men dominate cash crop production, regardless of agricultural system. Men dominate animal draft powered tillage methods, regardless of agricultural system. Women are more active in manual weeding and tillage regardless of agricultural system. Gender of household head did not seem to affect the ability of the household to practice oxen-ripping. This was because male labor from within the households was drawn upon. Strong cultural norms militate against women's routine use of animal draft powered agricultural implements, even when women individually or jointly own them. Survey results showed that spouses commonly jointly owned livestock, more frequently than sole ownership by men or women ($F = 38.18$, $p < 0.05$). Farming implements were similarly jointly owned more than they were individually owned by male and female spouses ($F = 153.00$, $p < 0.05$). In some cases the gendered division of labor could be explained in terms of physical attributes of men and women; tasks requiring more physical strength were dominated by men while women took on tasks requiring less physical strength. Tedious and repetitive tasks, characterized by drudgery were left to women and children. These practices were supported by the reproduction of pervasive local narratives that women were better suited for tedious tasks because they were patient and conscientious. Notably, such narratives changed in cases of cash crops. For instance, men dominated tobacco and cotton growing, both of which are

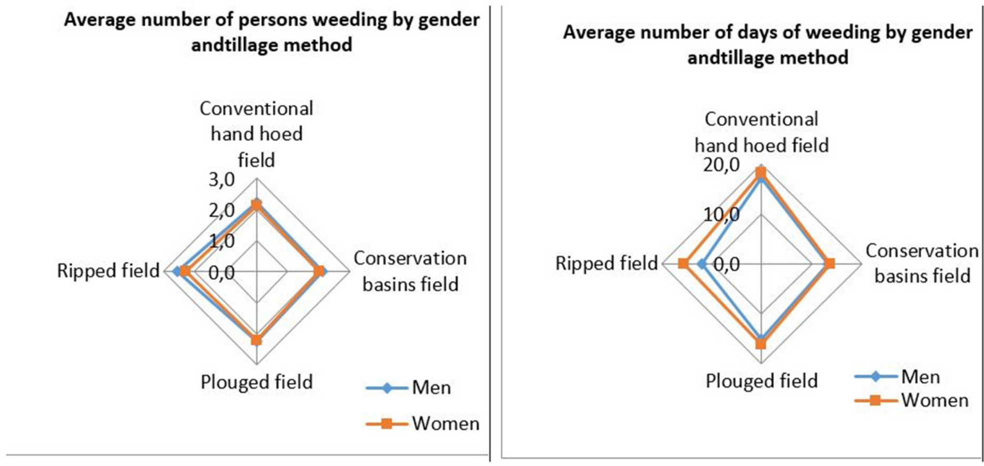

FIGURE 8 | Average number of adults involved in weeding and average days of weeding.

laborious. The desire for men to control cash incomes seemed to trump any other considerations.

Benefits Men and Women Farmers Derive From CA

Benefits of CA for men were perceived by 90% of the women's FGDs and almost 60% of the men's FGDs to be the retention of moisture in the basins. While all the men's FGDs mentioned higher crop yields as being a benefit of CA for men, only half the women's FGDs did (**Figure 9**).

A discussant from one of the men's FDG's held in Chipata phrased it as follows, "*We get a lot of production from just a small area. Maize production is very good in basins, especially during periods of low rainfall. The basins retain moisture for longer periods due to the crop residues.*" The superiority of basins during period of low rainfall was similarly espoused in other FGDs. For instance a discussant from the men's FGD in Chadiza said the following, "*No matter how little the rains are, basins always retain water. The basins retain water during droughts. Thus, they give higher yields. Higher yields than ripping and plowing.*" Superiority of basins in giving higher crop yields has been reported in previous studies on CA in Zambia (e.g., Umar et al., 2011; FAO and UNDP, 2020).

The women's FGDs similarly reported high crop yields and basins ability to retain water as beneficial to men. As an exemplar, one women discussant in Chadiza put her thoughts across as follows, "*No matter how little rains there are, basins always hold water. This helps with yields during droughts and helps the men to make money or to save money from not having to buy seed for replanting*" The women alluded to benefits for men that were not mentioned by any of the men's FGDs. These benefits are reduced labor requirements, fewer weeds in the basins, timely planting of crops, and an end to fires in fields. The women explained that men do not have to do as much because they rip (which requires less labor than making basins) and during weeding, they only have to weed inside the basins where there are fewer weeds. The unique answers from the men's FGDs were reductions in soil erosion, deforestation, and poaching, improved soil fertility, and reduced fertilizer costs. These benefits were essentially a repeat of the CA benefits extolled by the Community Markets for Conservation (COMACO), the largest agricultural-wildlife intervention in Eastern Zambia, and to which most discussants that gave these answers belong. A common narrative in the region is that poachers and charcoal producers switch to being CA farmers due to the higher benefits from that accrue to them from this switch. The higher crop yields from CA result in higher incomes as COMACO guarantees markets, including premium output prices to all compliant CA farmers.

On CA benefits for women, all the women's FGDs agreed that basins retaining moisture and higher yields in the basins helped them (**Figure 10**).

Examples of statements from women's FGDs on the benefits of CA for women are given below;

"*Basins store moisture and are good during drought periods. I get better yields from CA fields. I plant early … in November in my CA fields. Ripping is good because it is not as labor intensive.*"

"*Us we rip. It is good during droughts as the crops do well, even when the rainfall is below average.*"

"*With basins, we are assured of one ox-cart of harvest, regardless of rain situation.*"

"*basins retain moisture, as do crop residues. The fire breaks we make protect the fields from fires.*"

"*we get high yields even during droughts, because we use manure.*"

A few groups also mentioned soil fertility improvement, timely crop planting, reduced labor requirements due to soft soils in the basins, fewer weeds in the basins, and CA fields not being affected by fires. The soil fertility improvements were also implied by discussants that attributed the higher yields to the addition of manure in CA systems. Generally, women seemed more appreciative or more aware of the climate smart attributes of basins than the men. The men tended to focus on the higher yield benefits of CA. All the men's FGDs highlighted the

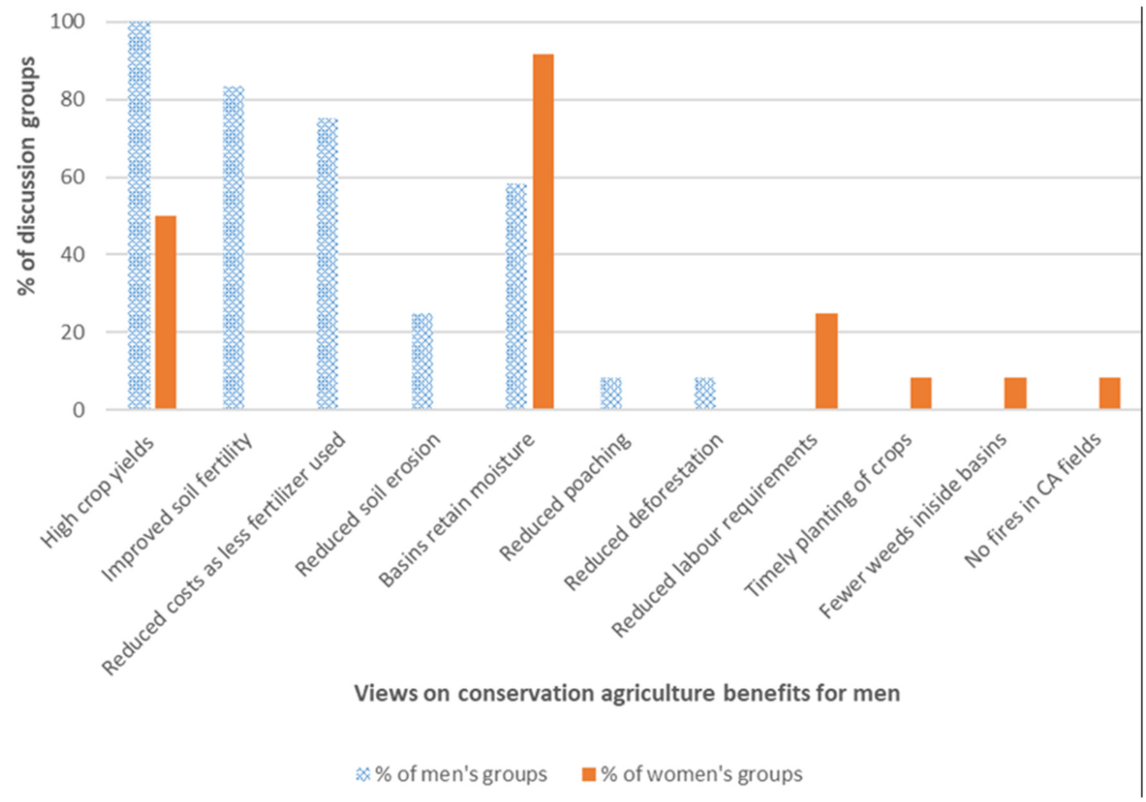

FIGURE 9 | Perceptions on benefits of CA for men.

higher crop yields under CA systems compared to conventional agricultural systems.

Moisture retention by basins makes the technology potentially important in adapting to climate change in the study region. Previous research has shown that during periods of intra-seasonal droughts, lower seasonal rainfall, and early off-set of rainy seasons, basins' capacity to hold moisture have made significant differences in crop yields (Umar and Nyanga, 2011) and subsequently, household food security for CA practicing farming households. With the predicted reduction in rainfall and increases in frequency of droughts in the Sub-Saharan Africa region (Asafu-Adjaye, 2014; Hamududu and Ngoma, 2020), a technology that enhances resilience to droughts deserves further consideration and up-scaling, provided that challenges associated with its adoption and use are addressed. Chineka et al. (2020) similarly concluded that CA adoption in Southern Africa has been successfully used to avert drought shocks, among other agricultural challenges.

Challenges Men and Women Farmers Face in the of Practice of CA

All the women's FGDs complained about the high weed pressure and high labor intensity required to make basins (**Figure 11**). In the words of one discussant in Mambwe, "*basins are hard to make. We cannot even manage two lima*[2]. *Weeds are also a problem. We weed manually here, we do not use herbicides.*" Chipata women discussants further noted the drawn out period during which they work on basins. The quote below illustrates this view.

"*Basins require a lot of labor. They are tiring to make. We have to start making basins immediately after harvest and do it slowly over time. But we need to focus on gardens in the dry season so we cannot manage both. We try to hire rippers and oxen.*"

Similar views were expressed in Katete. For example, "*Basin digging requires strong women. It is very hard work, characterized by drudgery. A household cannot even do one acre of basins without help. You have to hire labor. It is difficult to hire labor for basins. People refuse.*"

The women FGDs alluded to difficulties in accessing manure, lack of fertilizers, unavailability of *Chaka* hoes, lack of money for hiring labor, and lack of transport for manure. Some groups mentioned lack of availability of rippers, more termites/pests due to manure use, and dust from the creation of basins in the dry season. Water logging was barely mentioned although when it was mentioned, it was cited to be extremely problematic. A widowed discussed from Chipata reported the following, "*when it rains a lot, there are problems of water logging. I hired labor*

[2] A Lima is a locally popular measure of area. It represents 50 × 50 m area.

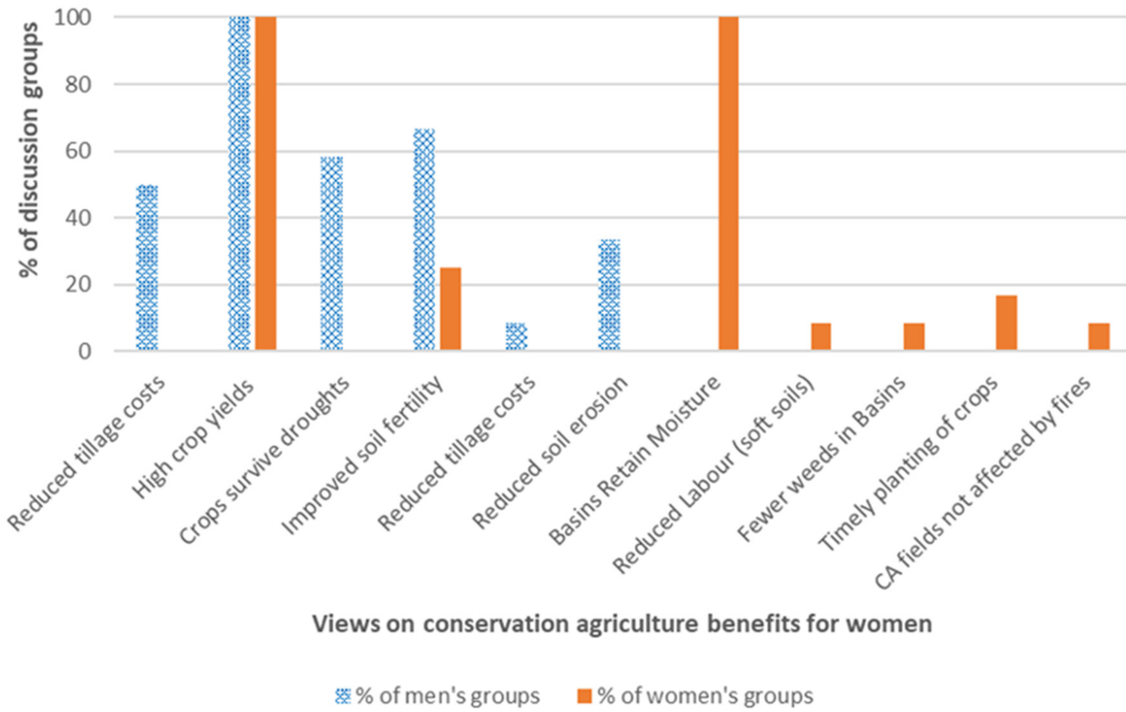

FIGURE 10 | Views on benefits of CA for women.

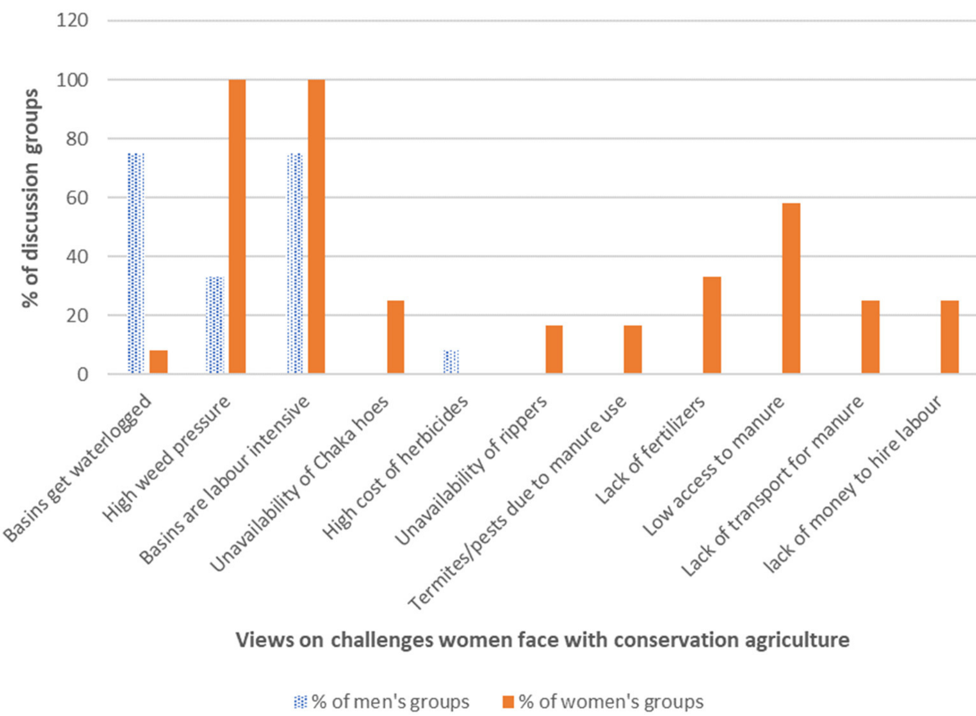

FIGURE 11 | Views on challenges of conservation agriculture for women.

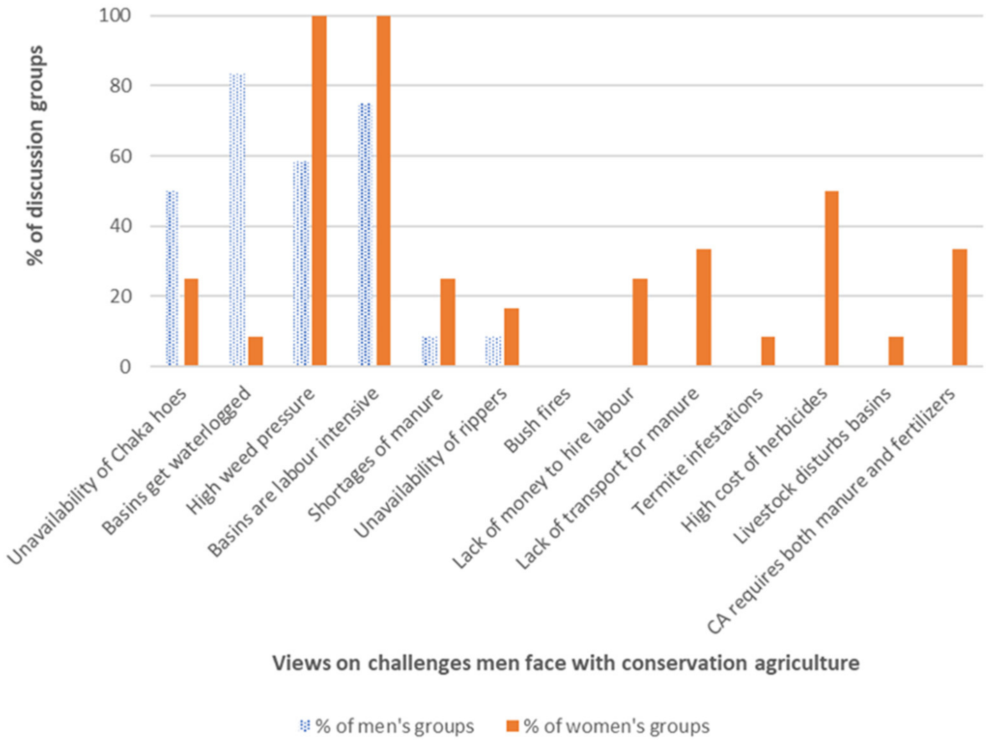

FIGURE 12 | Views on challenges of conservation agriculture for women.

for two acres but it rained a lot so I lost out. For those of us who are alone, it is hard to cultivate large areas. We may plan to but we fail. Weeds are a huge problem. We have to weed thrice in a season." Essentially, the women highlighted several challenges related to limited access to external inputs such as herbicides, fertilizers, manure and farming implements such as rippers and *Chaka* hoes. This reflects fundamental challenges that characterize smallholder farmers in Zambia, and are not limited to CA.

The men's FGDs highlighted the high labor requirements and drudgery associated with making basins and basins getting water logged as challenges for women more frequently than any other challenges (**Figure 11**). Less than half of the men's FGDs observed that weeds were a problem for women. A few linked weeds to cost of herbicides. In Chipata, one discussant summed up this thinking as follows, "*Weeding is a problem. We have been trained to use herbicides. Those with money buy herbicides*" Curiously, men did not perceive challenges associated with hiring labor for digging basins or the unavailability of *Chaka* hoes as challenges women faced. Overall, men mentioned only four challenges for women, while women outlined ten challenges for themselves. The men reported water logging as a challenge for both men and women, but the women barely mentioned it.

All women FGDs thought men were equally afflicted by the high labor demands and weed pressure associated with basins (**Figure 12**). Overall, women identified twice as many challenges faced by men as the men themselves did. Some of the women's FGDs brought up the issue of accessing and transporting manure to fields. The women mentioned three challenges related to manure while the men did not mention any. Women are more likely to face access to manure challenges than men because women are less likely to own livestock and consequently animal draft powered transportation such as ox-carts.

Basins getting waterlogged and being hard to make were prioritized as challenges men face, by the men's FGDs (**Figure 12**). A representative view from the men's FGDs in Mambwe is this, "*it is very hard to do one Lima. It is hard work to do basins during the dry season. It is better if one can afford to hire labor for making basins. Weeds are problematic too, in manual weeding especially.*" Similar views from Chipata on the weariness men feel when making basins, "*For basins, one cannot do them alone. There is need to hire labor. We have challenges doing this. A man cannot do three acres alone. There is need for something else … not Chaka hoes and rippers. Something that saves labor. Because these two are difficult to use.*" Half the men's FGDs remarked on the difficulty of accessing *Chaka* hoes. They saw this as a challenge limited to men because they had not cited this as a challenge facing women. This was possibly because they perceived accessing of Chaka hoes to be men's responsibility, in line with menäs culturally assigned roles as household heads.

The men reported water logging in basins as a challenge for both them and the women, but the women barely mentioned it. Both men and women mentioned weeds as a challenge for both men and women. Weeds are a notable and widely reported challenge in CA systems. Due to minimum tillage, weed pressure increases in CA systems. CA promoters in Zambia initially recommended that weeding be done up to six times in a season. However, CA households found this recommendation impossible to achieve. Recently, there has been an increased emphasis on the correct use of chemical herbicides in CA systems by many CA promoters. Herbicide use is challenging for women farmers for economic and socio-cultural reasons; women farmers generally lack access to herbicides as they are too costly for them to buy and they do not have access to credit facilities. Women are discouraged from handling herbicides due to their (women's) reproductive roles of childcare and food preparation. Most communities frown upon women carrying herbicide sprayers as this is seen to be very physically taxing work that should be left to the men. Women are only expected to spray herbicides when they do not have access to male labor. The men's FDGs reported norms against married men letting their spouses to apply herbicides. They explained that this was considered ill-treatment of spouses.

CONCLUSION AND POLICY IMPLICATIONS

Men and women smallholder farmers in Eastern Zambia have experienced climate change. Many smallholder farmers have adopted conservation agriculture (CA) to, *inter alia*, adapt to climate change. Although only one attribute of CA was explicitly mentioned as having climate resilience benefits, that is, moisture retention in basins, the emphasis on timely planting has climate resilience benefits too. There is room for CA to serve as a climate smart agricultural system for both men and women smallholder farmers in eastern Zambia. However, this will require addressing the challenges mentioned, most commonly weeds, high labor demands, access and transport for manure, and low accessibility to CA farming implements. There is need to pay attention to the gender differences in CA benefits and challenges. Further research is recommended on how rip lines could be adapted to enhance their moisture retention capabilities. Since rip lines are not made manually, the high labor demands and drudgery associated with basin making are not a bottleneck for this tillage method.

The reported shortening of the rainy season has important implications for farmers. A shorter cropping season and late on-set of the rainy season entail that farmers have to change the crops or crop varieties and change the planting dates. This further impinges on household labor allocations and decision making about crop choices. There is also need for timely access to weather forecasts so that farmers will know when to plant and what crops (or crop varieties) to plant. Information about rainfall distribution being made available to farmers at the start of the farming season would aid their decision-making.

The study finds nuanced experiences with CA, including its benefits and challenges based on gender. Members of each gender know more about issues that fall within their domain, from experience and may only have anecdotal knowledge issues relating to the other gender, and thus do not sufficiently appreciate the challenges. This was especially evident for challenges that were cited by members of one gender as applying to them, but failed to mention it as a challenge for the other gender. Gender differences in problem perceptions highlight the limitations of gender-neutral interventions and the importance of gender responsive research. Agricultural development interventionists are encouraged to better understand how CA and other agricultural innovations in general, differentially affect men and women farmers and to pay close attention to such nuances to maximize benefits for all gender groups. There is an urgent need to address the challenges that characterize smallholder agriculture in Eastern Zambia, in order to enhance the climate adaptation benefits of CA. The CA package for Zambia should include access to timely climate information and climate informed crop choices.

DATA AVAILABILITY STATEMENT

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

AUTHOR CONTRIBUTIONS

The author confirms being the sole contributor of this work and has approved it for publication.

FUNDING

The fieldwork was funded by the World Bank Group and TerrAfrica through the study on traditional constraints and less traditional or behavioral constraints for women participation in Agricultural and Forest Management in Zambia. The Nordic Africa Institute supported the write up of this work through its African Scholars Fellowship.

ACKNOWLEDGMENTS

Many thanks to Pablo Cesar Benitez (Senior Economist, ENB GP) and Sibani Karki (Gender Specialist ENB GP) and Progress H. Nyanga (Senior Lecturer, University of Zambia) for their contribution to the study.

SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fsufs.2021.748300/full#supplementary-material

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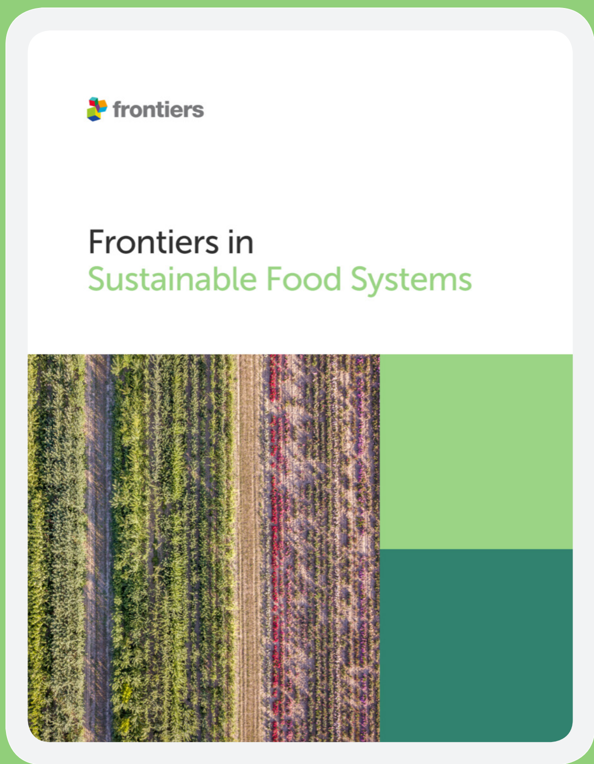

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