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Achieving a Climate-Change Resilient Farming System through Push–Pull Technology: Evidence from Maize Farming Systems in Ethiopia

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Abstract: Building climate-resilient farming systems is important to promote the sustainability of agriculture at the global level. Scaling-up agroecological approaches in main staple crops, such as maize, is particularly important in enhancing the climate resilience of millions of smallholder farmers in developing countries. In this regard, push–pull technology (PPT) is an ecological approach to a farming system that aims to improve the climate resilience of maize producers in a smallholder mixed farming system. PPT is primarily designed to control pests and weeds in an ecofriendly approach, to improve soil fertility, to improve livestock feed, and to increase farmers' incomes. In this study, we compared the level of climate resilience between PPT maize farming systems and non-PPT maize farming systems in southern Ethiopia. Using the Food and Agriculture Organization of the United Nations (FAO) Self-Evaluation and Holistic Assessment of Climate Resilience of Farmers and Pastoralists (SHARP), we measured 13 agroecosystem indicators of climate resilience and compared the degree to which the two farming systems differ in their level of resilience to climate change. The results indicate that PPT farming systems are more climate-resilient than their non-PPT counterparts. PPT maize farming systems had a significant impact on 8 out of the 13 agroecosystem indicators of climate resilience. To harness the full benefits of PPT, governmental extension agents, NGOs, and agricultural researchers should promote PPT-based maize farming systems. The promotion of PPT needs concerted efforts and strong national coordination in solving PPT implementation barriers, such as improving access to input and output markets and animal health services.

Keywords: agroecology; climate change; farming system; maize; push–pull technology; resilience; SHARP

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1. Introduction

Developing agricultural systems that are resilient to extreme weather events, diseases, weeds, and insect pests is essential for ensuring climate-resilient and sustainable food production. However, building a resilient farming system and increasing food production sustainably is a longstanding challenge for smallholder farmers in Sub-Saharan Africa (SSA) [1,2]. Climate change most likely will increase the threat from biotic and abiotic factors to farming systems in the region [3]. For example, an increase in temperature induced by climate change encourages weed and pest growth [4]. The threat of invasion by fall armyworms and Striga weeds is increasing on maize-producing farmers in the region [4,5]. The impacts of abiotic factors such as land degradation and drought have also been increasing [6]. Furthermore, non-climate-related shocks such as low crop prices and health issues further exacerbate the vulnerability of farmers in the region. Preventing stresses and shocks is often impossible [7,8], but building resilient farming systems offers a pathway to reduce the vulnerability of millions of smallholder farmers in the region.

Resilience is widely understood as the ability of a production system to recover, reorganize, and evolve following external stresses and disturbances [9]. In a farming system, improving agricultural productivity is important. However, improving productivity alone may not improve the resilience of farmers because resilience needs the ability to cope with diverse shocks on multiple timescales [9,10]. Interventions with a one-sided focus on improving agricultural productivity can potentially contradict the goal of building resilience [11]. The use of agrochemicals, for example, can increase the yielding of crops in the short run. However, agrochemicals can deteriorate the ecosystem and soil health, reducing crop yields in the long run [12,13]. Building resilience requires striking a balance between improving productivity and sustaining the resource bases of farming systems [9]. Thus, identifying the vulnerabilities within a farming system and taking actions on these vulnerabilities in ways that promote more sustainable farming practices are indispensable [9,14].

Agroecological measures, such as diversification of agroecosystems through polycropping, integrated crop-livestock production, and agroforestry systems, are often considered important approaches to strengthen the resilience of farming systems [15,16]. In designing resilient farming systems, agroecological measures should be accompanied by organic soil management, water conservation and harvesting, and enhancement of agrobiodiversity [15,16]. In effect, such agroecological farming systems help to reduce the risks of pests and diseases while improving water availability and the quality of the soil by improving soil water retention and organic matter. Agroecological approaches are important to reduce climate vulnerabilities in the food production systems as they help to foster biodiversity conservations and eco-friendly farming [17–19]. Studies suggest that enhancing resilience in the most important food production systems such as maize production can have a greater impact on ensuring the resilience of the farming systems in SSA countries [16]. Maize, which is the most widely cultivated staple crop in Africa, is vulnerable to extreme weather events. Therefore, promoting agroecological maize farming systems through push–pull technology can be an important pathway for a more resilient food production system in SSA countries. The push–pull technology was selected as an appropriate agroecological approach for small holders due its multiple benefits, including high-quality animal feed, biological pest protection, conservation of soil moisture, and improving soil health.

Push–pull technology (PPT) is an agroecological approach for integrated pest management that uses a combination of behavior-modifying stimuli to manipulate the distribution and abundance of insect pests and/or natural enemies [20]. PPT has been promoted in East Africa to control cereal stem borers and Striga and to improve soil fertility and animal feed. PPT involves intercropping cereal crops (maize or sorghum) with a forage legume, Desmodium species, and planting a grass, Brachiaria species, as a border crop [21]. Fall armyworm and stem borers are attracted to Brachiaria, a trap plant (pull), and are repelled from the main cereal crop using a repellent legume intercrop (push), Desmodium. Desmodium produces a smell (semiochemical) that stem borer moths do not like; hence, it pushes the stem borers away from the maize or sorghum. Desmodium root exudates effectively control parasitic Striga weed by causing abortive germination [22]. Desmodium also improves soil fertility through nitrogen fixation, moisture conservation through natural mulching, improved biomass, and control of erosion [22,23]. Both Desmodium and Brachiaria provide high-value animal fodder, positively impacting milk production and animal health. PPT also helps to diversify the income sources of farmers by allowing them to earn additional income from the sale of fodder and seeds for the two companion plants. PPT renders the mixed crop-livestock production system of smallholder farmers more resilient to climate change [22,23].

Existing studies on PPT have focused on its adoption factors and economic and welfare benefits. Studies show that gender, perceptions of Striga severity, technology access and awareness, and input market access are the most important factors in determining the adoption of PPT [24,25]. Amudavi et al. [26] suggest that strong institutions for input marketing help to increase PPT uptake and expansion. Regarding the benefits, several studies have shown that farmers who adopt PPT managed to control pests, increase their crop yield, improve milk production, and improve soil fertility [20,24,27–30]. To our knowledge, no study has documented the impact of PPT on climate resilience. This study, therefore, for the first time, revealed the contribution of PPT to climate resilience. The objective of this study was to examine the contribution of PPT toward improving the climate resilience of maize-based farming systems to different stresses and shocks in southern Ethiopia. The paper compares the resilience of PPT farming systems with conventional farming systems using the Food and Agriculture Organization (FAO)’s Self-Evaluation and Holistic Assessment to Climate Resilience of Farmers and Pastoralists approach (SHARP$^+$). By doing so, this study makes two important contributions. First, it provides insights into the long-term impacts of PPT by examining the link between PPT and a long-term outcome variable, resilience to climate change. The existing studies on PPT’s impacts are mostly focused on short-term outcome variables such as crop yield, income, milk production, soil fertility, and control of pests, e.g., [13,20,27]. Empirical information that links PPT and the resilience of farming systems would help to promote the widespread adoption of PPT. Furthermore, such empirical information would help to uncover mismatches between the needs of vulnerable communities and PPT, providing insights into potential leveraging points to further improve PPT. Second, this study contributes to the literature on the application of a new methodology to assess the climate resilience of farming systems. The study used a mixed-method approach, combining a new tool to measure resilience developed by the Food and Agriculture Organization (FAO) called the Self-Evaluation and Holistic Assessment to Climate Resilience of Farmers and Pastoralists (SHARP$^+$) survey tool with focus group discussions (FGDs). Using this approach enabled us to assess the level of climate resilience of PPT and non-PPT maize farming systems.

The rest of this paper is structured as follows. In Section 2, we discuss the materials and methods. In Section 3, we present the results, while in Section 4, we discuss the findings in relation to the previous studies. We end by discussing the conclusions and policy implication sections of the paper.

2. Materials and Methods

2.1. Description of the Study Sites

The study was conducted in four districts in southern Ethiopia: Abeshgie, Atote Ulo, Hawassa Zuria, and Tolay (Figure 1). The districts were PPT intervention areas of the International Centre of Insect Physiology and Ecology *(icipe)* since 2016. The Abeshgie district has an altitude range from 1500 to 2900 m above sea level, with an annual mean temperature range from 25 °C to 13 °C and a mean annual rainfall range from 1000 to 1500 mm. The Atote Ulo district has an altitude range from 1554 to 2149 m above sea level, with a mean temperature range from 17^{0}C to 20^{o}C and a mean annual rainfall range from 857 to 1085 mm. The Hawassa Zuria district has an altitudinal range from 1700 to 1850 m above sea level, with an annual mean temperature range from 30 °C and 17 °C, and a mean annual rainfall of 1015 mm. The Tolay district has an altitude range from 1100 to 1600 m above sea level, with a mean temperature range from 21 °C to 30 °C and a mean annual rainfall range from 400 to 900 mm/year. In all areas, farmers practice mixed crop–livestock farming, and maize is the dominant crop.

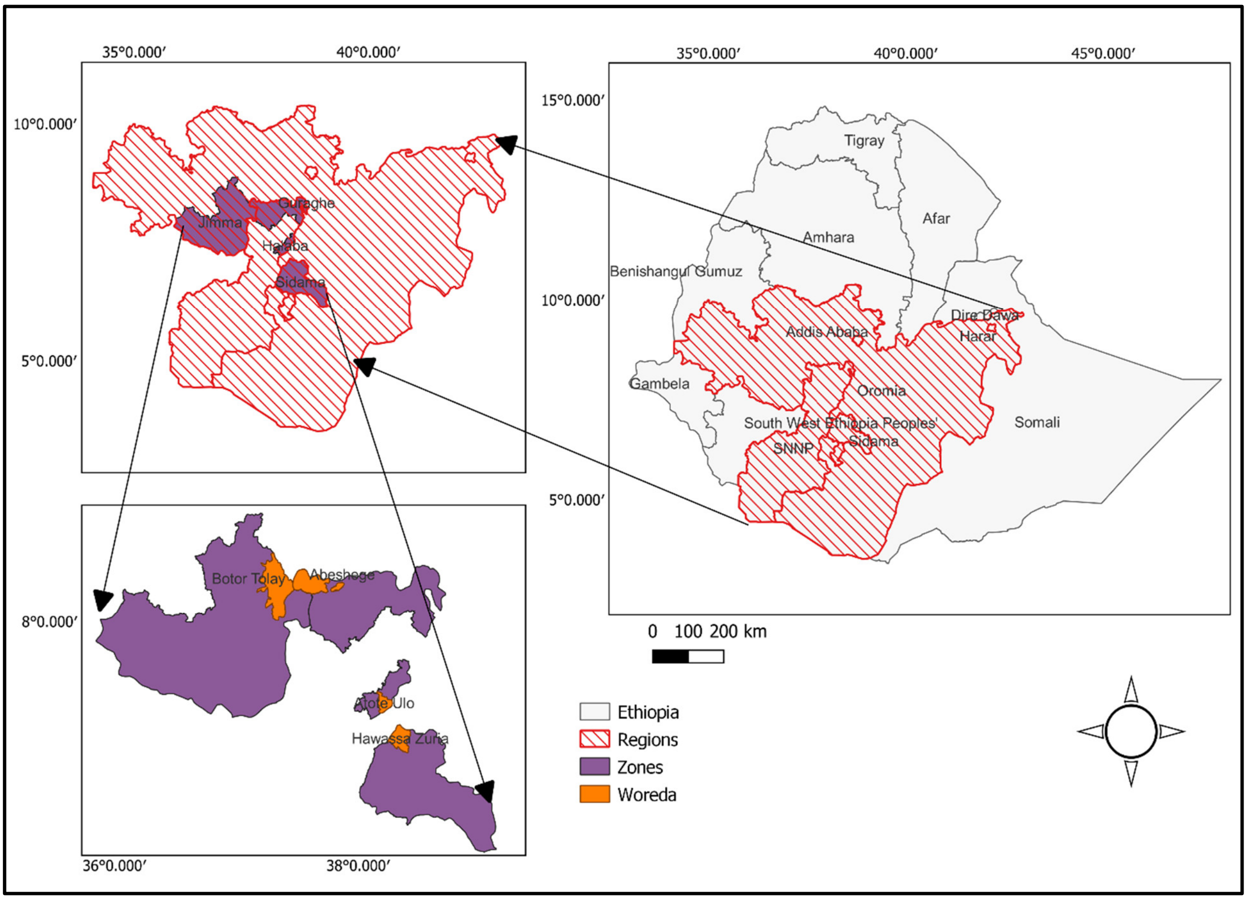

Figure 1. Study area.

2.2. Data Sources and Sampling

The data sources for this study originate from a cross-sectional household survey and focus group discussions (FGDs). Studies that compared resilience across groups of participants such as farming systems, communities, and institutions often rely on a cross-sectional household survey e.g., [31,32]. Due to methodological uncertainties in measuring resilience, the survey should be complemented by participatory approaches such as focus group discussions, which help to capture qualitative insights [32–34]. On the other hand, studies that focused on analyzing changes in resilience over time have used panel data, e.g., [35,36]. While panel data offers clear benefits, its data collection is, however, difficult to coordinate and costly in terms of both time and resources. In this study, we followed the former approach as it fits with the objective of the study. Before undertaking the survey and FGDs, our team conducted a one-week scoping study in July 2021. The scoping study provided insights into PPT adoption status and general information about farmers' agronomical practices, access to infrastructure, and farming systems. We applied these insights as input for the preparation of the survey and FGDs.

Our household survey data were obtained from 301 farmers in September 2021. We utilized a structured questionnaire of the Self-Evaluation and Holistic Assessment to Climate Resilience of Farmers and Pastoralists (SHARP^{+}) tool, which is discussed in the next subsection. The participants were selected from twenty-five villages across four districts (Table 1). We purposively selected the villages considering PPT interventions by *icipe* and captured heterogeneities in sociodemographic situations. We then randomly selected the survey participants from the roster of PPT adopters and nonadopters in the selected villages. The data were collected by experienced and well-trained enumerators. In each district, *icipe* trained farmers on the benefits and agronomic practices of PPT. About 30% of the farmers in the Hawassa Zuria district use PPT to enhance their maize and livestock production [28]. However, there are still many other farmers who have not yet adopted the technology. Therefore, comparing farmers who are using PPT with those who are not using PPT is possible. Of the 301 sample respondents, 157 farmers were PPT adopters, while 145 farmers were PPT nonadopters.

Table 1. Respondents' distribution.

Region	Zone	Woreda	Number of Villages	No. of Respondents		Number of FGDs
				PPT-Adopters	Non-PPT Adopters	
Oromia	Jimma	Tolay	2	10	8	3
Sidama	Hawassa Zuria	Hawassa Zuria	17	116	107	3
SNNP	Gurage	Abeshgie	4	21	21	2
	Halaba	Atote Ulo	2	9	9	1
Total			25	157	145	9

Nine FGDs were undertaken in the study districts. The FGDs focused on PPT adoption and its actual and potential benefits in building climate resilience for farmers (Table 1). Consistent with SHARP, the FGDs also captured farmers' perceptions of the links between SHARP's climate resilience indicators and the benefits and potential downsides of PPT. To capture diverse perspectives, we conducted the FDGs for three different types of participants: adopters, nonadopters, and disadopters of PPT. Eight to eleven participants attended each FGD. A checklist of discussion questions was used to guide the FGDs.

2.3. Self-Evaluation and Holistic Assessment to Climate Resilience of Farmers and Pastoralists (SHARP$^+$)

SHARP is a participatory climate resilience assessment tool that was developed by the Food and Agriculture Organization (FAO). SHARP helps farmers identify, measure, and prioritize actions to improve resilience to climate change [9,37]. The approach assesses climate resilience based on the knowledge and priorities of farmers [37]. SHARP considers farmers' traditional knowledge, skills, and practices, as well as governance systems, as a key for building and strengthening the resilience of farmers. In the SHARP approach, the respondents state the adequacy and the level of importance to the different aspects of their livelihood. This information allows an assessment of farmers' perceptions, behaviors, and priorities in enhancing their resilience to climate change. The SHARP approach allows us to compare and draw inferences about the impact of adopting different farming systems on the resilience of farming households [9,37].

Compared to other resilience measurement tools, such as the multidimensional index approach of TANGO International [38] and the Resilience Indicators for Measurement and Analysis (RIMA) [39], the SHARP approach provides comprehensive assessments, as it assesses resilience by capturing both quantitative and qualitative information. The SHARP approach considers resilience as a multidimensional concept that includes the complex interactions of agronomic practices and environmental, social, economic, and government forces in farming systems. In this study, we employed the most updated version of the SHARP survey tool, SHARP$^+$ [37]. As shown in Table 2, the SHARP$^+$ survey was developed to measure the 13 behavior-based climate resilience indicators of [40]. In the SHARP$^+$ approach, the quantitative and qualitative answers given by farmers and their self-assessed priority areas are transformed into numerical scores that reflect the 13 behavioral-based indicators of resilience. For each indicator, the differences in SHARP$^+$ scores reflect the differences in the level of resilience to climate change.

Table 2. Descriptions of the thirteen behavior-based indicators of resilience for agroecosystems based on Cabell and Oelofse [40].

	Descriptions
Socially self-organized	The social components of the agroecosystem are able to form their own configuration based on their needs and desires
Ecologically self-regulated	Ecological components self-regulate via stabilizing feedback mechanisms that send information back to the controlling elements
Appropriately connected	Connectedness describes the quantity and quality of relationships between system elements
Functional and response diversity	Functional diversity is the variety of ecosystem services that components provide to the system; response diversity is the range of responses of these components to environmental change
Optimally redundant	Critical components and relationships within the system are duplicated in case of failure
Spatial and temporal heterogeneity	Patchiness across the landscape and changes through time
Exposed to disturbances	The system is exposed to discrete, low-level events that cause disruptions without pushing the system beyond a critical threshold
Coupled with local natural capital	The system functions as much as possible within the means of the bio-regionally available natural resources base and ecosystem services
Reflective and shared learning	Individuals and institutions learn from past experiences and present experimentation to anticipate change and create desirable futures
Globally autonomous and locally interdependent	The system has relative autonomy from exogenous (global) control and influences and exhibits a high level of cooperation between individuals and institutions at the more local level
Honors legacy	The current configuration and future trajectories of systems are influenced and informed by past conditions and experiences
Builds human capital	The system takes advantage of and builds resources that can be mobilized through social relationships and membership in social networks
Reasonably profitable	The segments of society involved in agriculture are able to make a livelihood from the work they do without relying too heavily on subsidies or secondary employment

To accurately assess the diverse benefits of using PPT, we adapted the SHARP$^+$ survey tool to the study areas' farming context. The original SHARP$^+$ survey contains questions organized in 33 modules, of which 17 modules are mandatory for computing the 13 behavior-based indicators of resilience in Table 2. To ensure alignment with the theoretical background of SHARP, we maintained the 17 core modules. The remaining 16 optional modules were then assessed to adjust SHARP to suit the purpose of this study. After multiple rounds of discussions, the research team identified five modules relevant to the objectives of this study from the 16 nonmandatory modules. These modules comprised weed species and management, livestock nutrition and health, soil quality and land degradation, access to information on weather and climate change adaptation, and major productive assets modules. Of the 33 modules of the SHARP$^+$ survey, 22 modules were selected. Furthermore, we added a new thematic module: maize production. This new module captures maize farming practices in the study areas. As maize is the most important crop in the study areas, a climate-resilient maize farming system is essential. This module, therefore, captures the knowledge, production techniques, crop varieties, market access, and other important factors in connection to maize farming and production. To remain consistent with the SHARP approach, the questions in the newly added module pertain to agronomic, social, environmental, and economic domains. The questions also explore both the technical resilience component and the self-assessed adequacy component of SHARP.

We maintained the ten-point scoring scale of the SHARP+ approach in each module. We checked the applicability of the scorings and adjusted them to better fit the context of the study. For the questions in the newly added thematic module, we developed the scores in a way that fit the questions' response options vis-à-vis the context of the study. In this regard, the insights obtained from a scoping study that was conducted before this study helped us to adjust the scoring. Building on these adjustments, we adjusted the original SHARP$^+$ tablet-based data collection application**.** Before using the adapted SHARP survey, we pretested and slightly rephrased the questions to make them more understandable to the respondents.

Consistent with SHARP$^+$, the unit of analysis is the farming system [9,37]. Distinct from a single farm, a farming system is a population of individual farms that have similar characteristics in terms of resource bases, livelihoods, and constraints [40]. A farming system contains households with the farm and its external environments, i.e., natural, institutional, and socioeconomic environments [40]. In this study, the farming system represents maize cultivation and contains two categories based on agricultural management practices: maize farming that uses PPT (A) and conventional maize farming (B) (see Figure 2). We evaluated whether the PPT-based maize farming system produces a higher degree of climate resilience than the conventional maize farming system. The PPT farming system is a farming system that contains households that adopt PPT for its different benefits: pest control, soil fertility, seed production (Brachiaria and Desmodium), or fodder production. The conventional maize farming system constitutes households that have no experience using PPT.

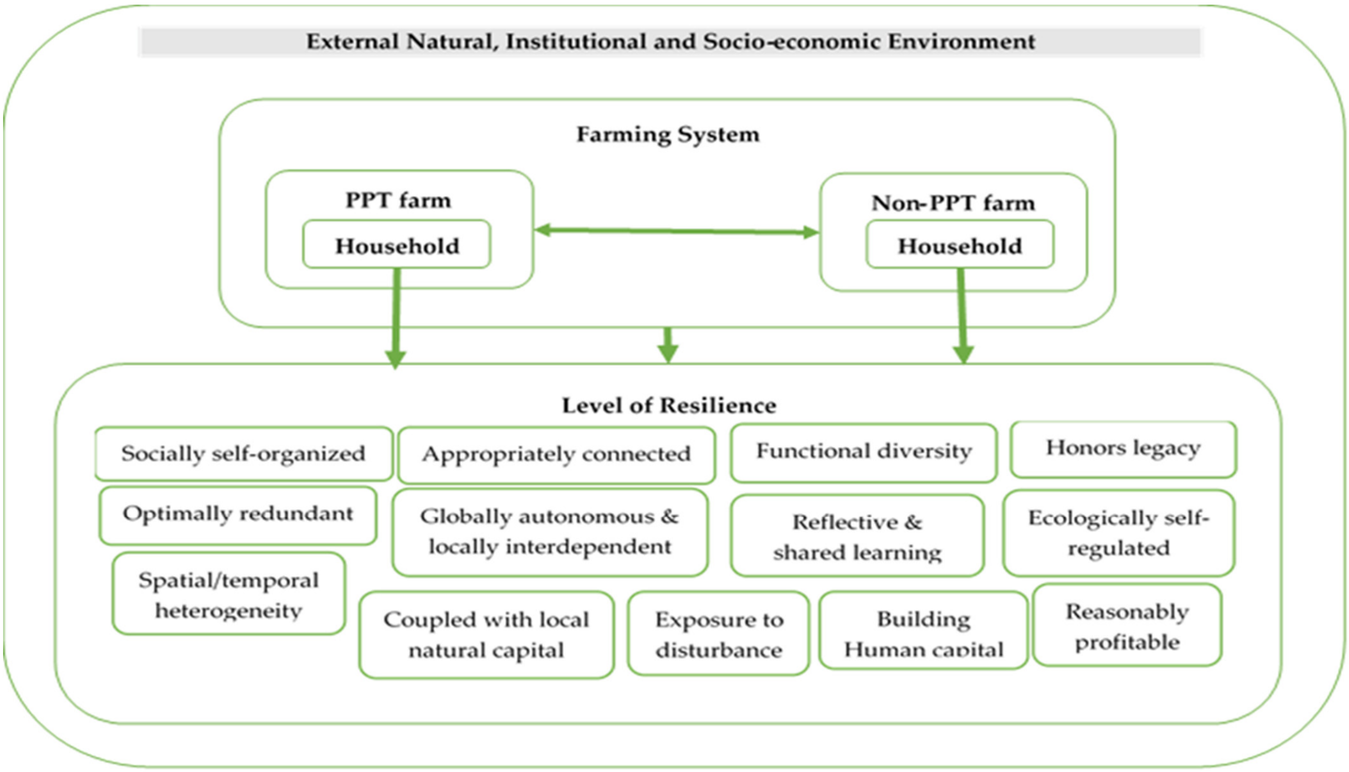

Figure 2. A farming system concept using a socio-ecological system approach, adapted from [9].

2.4. Data Analysis

Following Hernandez et al. [37], we calculated three resilience scores. The first resilience score consisted of the compound resilience scores, computed at the module level. The scores comprise the technical and adequacy scores for each question in the module. The compound resilience score ranges from 0 to 20, as it is the sum of the technical score (maximum 10 points) and self-assessed adequacy score (maximum 10 points). The compound resilience score can be categorized as low if the score is less than 7.00 points, as a medium if the score is between 7.01 and 12.00, and high if it falls between 12.01 and 20.00 [37]. The second resilience score consisted of the 13 behavioral-based indicators of climate resilience. Unlike compound resilience indicators, the 13 behavioral-based indicators were computed in the range of 10 points [37]. To calculate the scores for the resilience indicators, first, we computed the subcomponent scores and aggregated them by the 13 indicators. Then, we calculated a resilience capacity index using the 13 indicators of climate resilience by applying a factor analysis. Using the resulting weight from the factor analysis, we calculated the resilience capacity index. The approach helps to complement the farming system-level analysis with the analysis at the household level. Thus, the latter index helps to triangulate the results obtained from the farming system-level analysis. After calculating the three indices, we compared the two farming systems against the indicators of climate resilience using a two-way *t*-test.

A multiple regression model was employed to estimate the impact of a PPT farming system on the resilience capacity index of households. The regression model used is as follows:

$$y = \beta_0 + \beta_1 \mathrm{PPT} + \beta_2 X + \varepsilon,$$

where y is the resilience capacity index; PPT is a dummy variable that shows the maize farming systems where PPT = 1 if PPT-based maize farming system 0 otherwise.; and X is a vector of household characteristics, including the gender of the household head, age of the household head, family size, highest education level of the household head, and land access. Gender, age of the household head, education, and land access variables were measured as categorical variables, whereas family size was measured as a continuous variable. β_0, β_1–β_2, and ε represent a constant term, coefficients of household characteristics, and a standard error term, respectively. The coefficient of interest is β_1, which measures the impact of farmers' resilience to climate change. The regression model enables us to complement the results from farming system analysis with a household-level analysis.

3. Results

3.1. Socioeconomic and Farming System Characteristics

In this section, we present the results of the socioeconomic and farming system characteristics of the two farming systems. Table 3 shows the socioeconomic characteristics of PPT and non-PPT farming systems. The gender of the household head differed significantly between PPT farming systems and non-PPT farming systems, whereas the majority (85.05%) in both farming systems were male-headed households. Approximately 61% of the household heads' age ranged from 30 to 49 years, with no difference exhibited in the age ranges of the two farming systems. We also found no significant difference between the two farming systems in family size, with an average of 6.17 persons per household. However, the highest education level of the household head differed significantly, where PPT farming systems exhibited higher education levels than their counterparts. As for the number of agricultural activities between the two farming systems, on average, households engaged in 2.19 and 2.12 agricultural activists in PPT farming systems and non-PPT farming systems, respectively. The size of private land owned also differed between the two groups, where on average, households in PPT farming systems owned a relatively larger area of private land than their counterparts.

In diversifying agricultural activities, we observed that households in PPT farming systems were better at diversifying their agricultural activities than those in non-PPT farming systems (Table 3). The number of seasonal crops cultivated, and livestock species owned differed significantly between the two farming systems in favor of PPT farming systems, with an average of 3.66 seasonal crops cultivated and 1.02 livestock species owned per household. However, farmers in both farming systems showed no difference in the number of nonagricultural income sources; only 59.13% of the farmers earned income from nonagricultural income sources such as trading, remittance, and services. The number of productive assets owned differed significantly between the two groups, with an average of 5.84 productive assets.

Table 3. Socio-economic characteristics of the respondents.

Variables and Description	**PPT**	**Non-PPT**	**Mean**		
	N = 156	**N = 145**	**N = 301**	**X^2**	***t*-Test**
Gender					
Male	89.7	80.0	85.05	5.61 **	
Female	10.3	20.0	14.95		
Age of the respondent					
Less than 30 years	17.31	8.97	13.29		
30 to 49	58.97	63.45	61.13	6.17	
50 to 60	17.95	17.24	17.61		
Greater than or equal to 61	5.77	10.34	7.97		
Family size	6.08	6.27	6.17		−0.85
Highest educational level of the household head					
None	21.15	33.79	27.24		
Primary School	41.67	44.83	43.19		
Secondary	14.10	10.34	12.29	13.72 **	
High School	7.69	4.14	5.98		
Tertiary	10.26	4.83	7.64		
Vocational training	2.56	0	1.33		
Other non-formal education	2.56	2.07	2.33		
Number of agricultural activities	2.19	2.12	2.16		1.58 *
Land access: private land used for agricultural activities in ha					
Less than 0.5	28	40	68		
0.6 to 1.00	27	33	60		
1.01 to 3.00	88	63	151	8.45 *	
3.01 to 5.00	9	5	14		
More than 5.01	3	1	4		
Crop diversification: number of seasonal crops grown	3.76	3.55	3.66		1.81 **
Animal diversification: number of species owned	3.09	2.78	1.02		2.00 **
Income sources: nonagricultural income sources					
Yes	60.25	57.93	59.13	0.17	
No	39.75	42.07	40.87		
Productive assets: number of productive assists owned	6.07	5.6	5.84		2.74 ***

Statistical significance: * $p < 0.01$, ** $p < 0.05$, *** $p < 0.001$.

Table 4 shows the agronomical characteristics of the two maize farming systems. We observed that there were no significant differences between the two farming systems in the perceived maize yield changes over the last 3 years. The majority (73.09%) of the farmers reported an increase in maize yield, while the remaining 16% and 34% of the farmers reported a decrease in maize yield and a stable maize yield, respectively. Moreover, there were no differences in the type of maize seed cultivated by the two farming systems, and the majority (96%) of both farming systems cultivated an improved maize variety. However, the yield changes in fodder production differed significantly between PPT farming systems and non-PPT farming systems; approximately 52% of the households in PPT farming systems reported an increase in fodder yield, whereas this increase was only 30% in the non-PPT farming system.

Furthermore, Table 4 shows that on average, the households in PPT farming systems and non-PPT farming systems observed 2.07 and 2.03 different types of land degradation in their farmland, respectively. The number of degradation types was, however, not significant between the two groups. However, we observed significant differences in the number of soil quality improvement practices between the two farming systems, with an average of 3.79 land improvement practices. The perceived soil fertility changes in the farmland were also significantly different in favor of PPT farming systems; nearly 71% of the farmers in the PPT farming system reported an increase in the level of soil fertility, while this increase was approximately 64% for the farmers in the non-PPT farming system.

Table 4. Characteristics of farming systems.

Variables and Description	**PPT**	**Non-PPT**	**Mean**		
	N = 156	**N = 145**	**N = 301**	**X2**	***t*-Test**
Maize yield changes: yield changes in the last 3 years					
Increasing	75.64	70.34	73.09	1.84	
Decreasing	15.38	15.86	15.61		
The same	8.97	13.79	11.29		
Origin of maize seed: maize seed cultivated					
Only local seed	0.64	0	0		
Only improved/new seed	95.51	95.86	95.68	0.94	
Mix of local and improved seed	3.85	4.14	3.98		
Fodder production: yield changes from maize farmland					
Increasing	51.92	30.34	41.53		
Decreasing	32.69	29.65	31.23	25.36 ***	
The same	15.38	40.00	27.24		
Land degradation: number of land degradations observed on maize farmland	2.07	2.03	2.05		0.48
Soil quality improvement: number of actions taken to improve soil quality	3.97	3.58	3.79		1.95 **
Soil fertility: has soil fertility changed on maize farmland?					
Increasing	70.51	56.55	63.79		
Decreasing	16.02	22.07	18.93	6.47 **	
The same	13.46	21.37	17.27		

Statistical significance: ** $p < 0.05$, *** $p < 0.001$.

3.2. Compound Resilience Scores

For all 22 modules included in the SHARP survey, the mean compound resilience scores range from 8.35 to 15.07 for the water access indicator and community cooperation resilience indicator, respectively (Table 5). According to SHARP's resilience threshold level cf. [37], the mean scores for the compound resilience for both the PPT farming system and non-PPT farming system were in the category of medium and high resilience levels. Regarding the two farming systems, in 9 of 22 compound resiliencies, PPT farming systems scored at a higher resilience level, whereas the non-PPT adopters scored at a higher level for 6 compound resilience indicators only. Table 5 further reveals that 19 of the 22 compound resilience scores were significantly different between the PPT farming system and the non-PPT farming system. In all 19 compound resilience indicators, the PPT farming system exhibited a significantly higher level of climate resilience. However, there were no significant differences between the two farming systems regarding three compound resilience indicators: household health, weed management, and pest management.

Table 5. Compound resilience scores of the two farming systems.

	PPT N = 156		Non-PPT N = 145		*t*-Test	
SHARP$^+$ Modules	**Mean**	**Std. Dev.**	**Mean**	**Std. Dev.**	**Diff**	***t*-Value**
Household health	9.40	3.15	9.19	3.45	0.20	0.53
Ag activities	12.09	2.99	11.22	3.02	0.87 ***	2.51
Land access	12.65	2.28	12.12	2.36	0.52 **	1.95
Crop production	11.56	2.62	11.02	2.41	0.62 **	2.13
Maize production	11.09	2.77	10.17	2.62	0.76 ***	2.45
Weed management	14.48	2.18	14.30	2.15	0.07	0.29
Pest management	13.44	3.15	13.78	2.82	−0.03	-0.1
Livestock production	11.43	2.18	10.98	2.79	0.74 ***	2.48
Animal nutrition and health	12.15	2.99	11.80	3.29	0.71 **	1.92
Water access	8.93	2.65	8.35	2.52	0.58 **	1.89
Soil quality	12.04	2.47	11.32	1.97	0.48 **	1.84
Land management	12.59	2.12	12.32	1.95	0.34 *	1.46
Trees	10.67	3.78	10.11	4.07	0.67 *	1.48
Shocks	10.64	3.20	10.09	3.57	0.54 *	1.42
Access info weather	10.64	4.82	9.59	5.38	1.05 **	1.79
Access to market	9.57	2.13	8.91	2.72	0.65 **	2.32
Income expenditure	11.92	2.64	10.97	2.87	0.81 ***	2.56
Productive assets	14.23	1.95	13.75	2.10	0.53 **	2.21
Community cooperation	15.07	2.20	14.82	2.63	0.36 *	1.29
Group membership	9.92	3.70	9.25	3.86	0.65 *	1.57
Nutrition	11.69	2.78	10.84	2.79	0.71 **	2.2
Decision-making	10.46	2.46	9.58	3.25	0.79 ***	2.39

Statistical significance: * $p < 0.01$, ** $p < 0.05$, *** $p < 0.001$.

3.3. Thirteen Behavioral-Based Indicators of Climate Resilience

Figure 3 shows the mean scores of the 13 climate resilience indicators for PPT and non-PPT farming systems. The mean scores for 8 of the 13 agroecosystem indicators were significantly higher for PPT farming systems. PPT farming systems exhibited a significantly higher level of resilience for the socially self-organized, ecologically self-regulated, appropriately connected, functional and response diversity, spatial and temporal heterogeneity coupled with local natural capital, building human capital, and reasonably profitable indicators of climate resilience. However, for the remaining resilience indicators—optimally redundant, exposed to disturbance, reflective and shared learning, globally autonomous and locally interconnected, and honors legacy—there were no significant differences between the two farming systems.

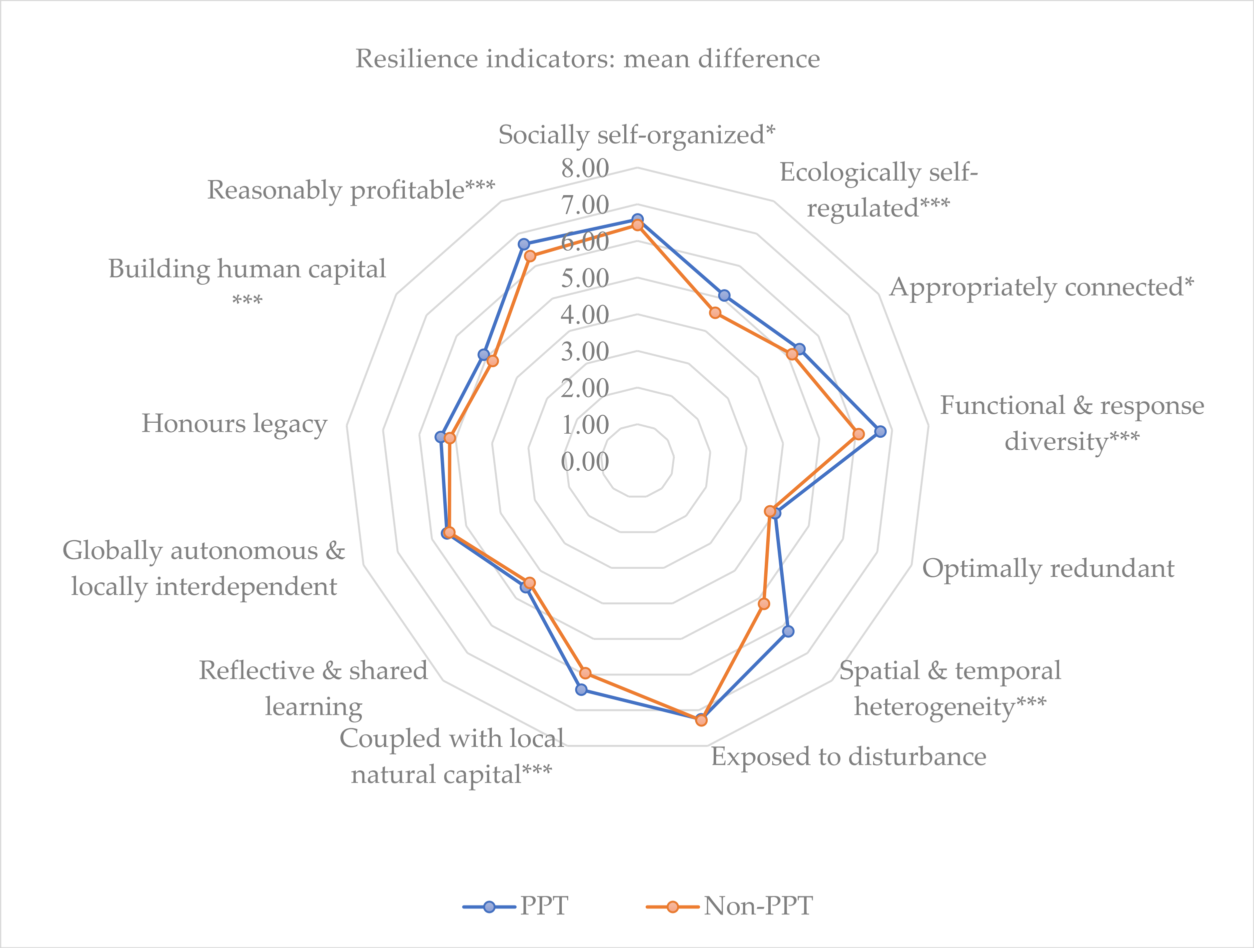

Figure 3. Mean scores for the 13 agroecosystem indicators for climate resilience of PPT and non-PPT farming systems. Significant differences determined by t-test are indicated as * $p < 0.01$, *** $p < 0.001$.

3.4. Resilience Capacity Index

The aggregate resilience capacity index generated using factor analysis of the 13 behavioral-based indicators was compared between the two farming systems. On a 10-point scale, the average resilience capacity index was 6.22 and 5.57 for the PPT farming system and non-PPT farming system, respectively. The t-test result shows that the resilience capacity index differed significantly between the two farming systems: PPT farming systems exhibited a significantly higher resilience capacity index level at $p < 0.001$ than non-PPT farming systems.

Table 6 shows the results of the regression model. As shown in the table, PPT farming systems had a significant positive effect on the resilience capacity of households ($\beta = 0.20$, $p < 0.10$). Compared to female-headed households, male-headed households were predicted to have a higher resilience capacity index of households with $\beta = 0.38$ ($p < 0.05$), whereas family size had no significant effect on the households' resilience capacity to climate change. Household heads with the highest education level of secondary and high schools were predicted to have a higher resilience capacity with $\beta = 0.38$ ($p < 0.10$) and $\beta = 0.64$ ($p < 0.05$), respectively. The size of private land owned also had significant positive effects on the resilience capacity of households.

Table 6. The effect of farming systems on resilience capacity index.

Resilience Capacity Index (y)	**Pooled (N = 301)**	
	Cof (β)	**t**
PPT farming system	0.20 *	1.80
Gender	0.38 **	2.32
Age of the respondent		
30 to 49	0.11	0.68
50 to 60	0.31	1.49
Greater than or equal to 61	0.06	0.23
Family size	0.01	0.13
Highest educational level of the household head		
Primary school/non-formal	0.15	1.05
Secondary	0.38 *	1.86
High school	0.64 **	2.48
Tertiary/vocational	0.21	0.92
Land access: private land in ha		
0.6 to 1.00	0.41 **	2.52
1.01 to 3.00	0.42 ***	3.03
3.01 to 5.00	0.80 ***	2.91
More than 5.01	0.07	0.15

Statistical significance: * $p < 0.01$, ** $p < 0.05$, *** $p < 0.001$.

In general, the results from the farming system and household level analyses showed that there are significant differences between the two maize farming systems. The results from the farming system analyses indicated that the two farming systems exhibited significant differences in the socioeconomic and farming system characteristics as well the two resilience indicator scores: compound resilience indicators and the thirteen behavioral-based indicators of climate resilience. In the household-level analysis, the PPT maize farming system was found to positively predict a higher resilience capacity index.

4. Discussion

In this study, we employed the SHARP approach to compare the degree of climate resilience between the PPT maize farming system and the non-PPT maize farming system in southern Ethiopia. The approach integrates environmental, economic, political, and social dimensions in assessing climate resilience, which allows us to perform a more comprehensive assessment of the degree of climate resilience of the two farming systems. Previous studies that focus on the climate resilience of farm systems also utilized the same approach to climate resilience, e.g., [31,34]. As stated by Choptiany et al. [41], resilience assessment of farming systems should acknowledge people's socioecological behaviors, which could be difficult to fully capture quantitatively. Therefore, in this study, we complemented the SHARP approach with FGDs, which allows us to draw more qualitative insights into the potential of PPT in enhancing the climate resilience of smallholder farmers.

The results on socioeconomic characteristics indicated that the number of male-headed households and the education level of the household head were higher in PPT farming systems than in non-PPT farming systems. These results are consistent with the findings of other studies; a meta-analysis by Guo, Ola [42], for example, shows that male-headed households and higher education levels of the household head are most likely to use new agricultural technologies. The findings of this study suggest that households headed by women and less educated women, or men lag in employing PPT farming systems. This result suggests that the gender and education of the household heads have important roles in the households' PPT adoption decision.

The results in Table 4 suggest that PPT farming systems can foster the diversification of agricultural activities. Compared to non-PPT farming systems, households in PPT farming systems were better at diversifying their agricultural activities. However, the average number of agricultural activities for the study area was approximately two agricultural activities per household, mainly crop and livestock production. As such, agroforestry, fishing, and beekeeping were not common agricultural undertakings in the area. Studies, e.g., [33,43], have indicated that a more diverse farming system is more resilient against climate change and environmental shocks. Therefore, it is reasonable to argue that PPT farming systems enhance the climate resilience of smallholder farmers by enabling them to diversify their agricultural activities. However, the mechanism through which PPT farming systems encourage the diversification of agricultural activities is ambiguous. One mechanism is to increase earnings from agricultural activities; households could invest the additional earning in other agricultural activities. Alternatively, households in PPT farming systems already have a positive attitude toward diversified agriculture, which is why they chose to employ PPT farming systems. This finding, however, requires further study to explain the link between PPT farming systems and diversifying agricultural activities.

The farmers in the study positively perceived the fodder production benefits of PPT farming systems but not the maize yield benefits. The households in PPT farming systems reported experiencing positive yield changes in their fodder production compared with the households in non-PPT farming systems. However, there was no difference between the two groups in their perceived maize yield changes. This result is contrary to previous studies, which reported that farmers held a positive attitude on the maize yield benefits of PPT. This finding can partly be attributed to the same maize variety cultivated by the households in the two farming systems; nearly 95% of the households in both groups cultivated an improved maize variety only, instead of a local maize variety or a mix of the two maize varieties. This result can homogenize the maize yield changes across the two groups. Combined with the insights from the FGDs, the results imply that farmers in the study area held a more positive perception of the fodder production benefits of PPT than the maize yield benefits of PPT.

The results on compound resilience indicators show that PPT farming systems were better in many of the indicators of climate resilience. In 17 of 22 indicators, PPT farming systems exhibited a higher degree of climate resilience than non-PPT farming systems. We, however, found no evidence on the positive impact of PPT on pest management and weed management compound resilience indicators. This finding is contrary to our expectations and the findings of many studies, e.g., [27,28,44], that reported a positive impact of PPT in controlling pest and weed infestations. This finding can partly be explained by the lack of a severe infestation of some types of weeds, such as Striga, in their farmland. In the FGDs, farmers mentioned that PPT helps them to prevent the infestation of different varieties of pests and weeds. For example, they reported that PPT suppresses Striga weed but found no incident of Striga infestation in recent years. This finding implies that PPT's benefit in controlling Striga weed did not materialize for the PPT farming system. In general, the results for compound resilience provide evidence that PPT farming systems have far-reaching benefits in improving livelihood conditions by enhancing, among others, agricultural diversification, crop production, livestock production, water access, and land management. As a result, PPT farming systems can be more resilient to the adverse effects of climate change and other shocks, such as environmental and production shocks.

Using the 13 behavioral-based indicators of climate resilience [40], this study has provided further empirical evidence on the comparative advantage of PPT farming systems over non-PPT farming systems. The indicators are the primary building blocks of the SHARP approach for assessing the climate resilience of farming systems. Thus, we suggest that providing a detailed separate discussion on each of the 13 indicators adds insights into elucidating the mechanism through which PPT impacts the climate resilience of farming systems. Furthermore, this approach makes the findings of this study more comparable with other similar studies that may use the SHARP approach. Now, let us direct the discussion to each of the 13 behavioral indicators:

Socially self-organized: The findings of this study reveal that PPT farming systems exhibited higher social self-organized ability than non-PPT farming systems. This finding implies that PPT farming systems facilitate farmers' participation in local associations, access to local markets, access to communal resources, and the use of internal coping mechanisms. PPT farming systems have a greater degree of intrinsic adaptive capacity, handling stresses and shocks with minimal external input [40]. However, a similar study by Heckelman and Smukler [34] on organic and conventional rice systems found no significant differences between the two systems for this indicator. The finding in this study can be attributed to the support mechanisms of *icipe* and its partners for PPT farming systems, which could encourage households to be more connected to agricultural extension workers and different social organizations. However, in the FGDs, the farmers in both groups reported limited access to markets, especially for input markets, including seeds for maize and companion plants (Desmodium and Brachiaria). To further reinforce the socially self-organized ability of PPT farming systems, encouraging the establishment of farmers' associations with PPT adopters can be a step forward. Such an association could help PPT farming systems solve their common problems, such as access to seeds for companion plants.

Ecologically self-regulated: PPT farming systems exhibited a significantly higher degree of ecologically self-regulated capacity than non-PPT farming systems. Thus, PPT farming systems rely less on external inputs, such as nutrients and water, to maintain the system than non-PPT farming systems. PPT farming systems use more perennial crops and nitrogen-fixing plants but fewer chemical inputs, which helps to exhibit a greater degree of ecological self-regulation, according to Cabell and Oelofse [40]. Our finding is consistent with previous studies, which reported a positive impact of PPT in reducing the use of synthetic fertilizer and chemicals [45] and in improving biodiversity [23,46]. Our finding is also comparable with the findings of Heckelman and Smukler [34]. Thus, our findings provide additional empirical evidence that PPT strengthens the capacity of farming systems to sustain themselves with much less need for external intervention in controlling pests and weeds and maintaining biodiversity and soil resources.

Appropriately connected: PPT farming systems exhibited a marginally higher level of resilience for this indicator. This finding implies that PPT farming systems have better access to seeds, market information, weather information, and veterinary services [40]; it also implies that PPT farming systems are better at exercising intercropping strategies. Contrary to our finding, a study by Heckelman and Smukler [34] on organic and conventional rice farming systems found no significant difference between the two farming systems for this indicator. In this study, however, the use of PPT can have direct and indirect effects on the indicator. Directly, PPT can influence the employment of intercropping strategies, as PPT is an agricultural technology that is based on intercropping strategies. Indirectly, the technical backstopping given to PPT adopters by *icipe* staff and its partners can also improve the connectedness of households with different actors in the community, which can help them to develop better access to agricultural inputs and services.

Functional and response diversity: PPT farm systems were better than non-PPT farm systems regarding functional and response diversity. This finding implies that PPT farming systems exhibited a higher level of diversity in inputs, outputs, income sources, markets, pest control approaches, and weed management practices [40]. This finding is consistent with the advantages of PPT reported in several studies on diversifying outputs, income sources, pest control approaches, and weed management [16,28,29,44,47]. Compared to conventional farming systems, several studies have also reported a positive effect of PPT farming systems in enhancing biodiversity in farm systems [23,46]. The participants in the FGDs also revealed that animal feed and seed production (for the companion plants) were the main incremental outputs of PPT compared to the conventional maize farming system. Our finding is also comparable with the study of Heckelman and

Smukler [34]. Our results thus provide additional empirical evidence, as PPT farming systems have more diverse mechanisms to address pest and weed controls and have more diverse farm inputs and outputs than conventional maize farming systems. Higher functional and response diversity serves as a buffer against perturbation in the farm system, which helps the system to be more resilient to climate change.

Optimally redundant: The two farming systems exhibited no significant differences in this indicator. Moreover, both farming systems scored a relatively lower degree of resilience on this indicator compared to the other resilience indicators. This finding implies that the two farming systems have no multiple backups in cultivating varieties of crops, having equipment for various crops, sourcing nutrients from multiple sources, and obtaining water from multiple sources. In the FGDs, farmers mentioned that farm inputs such as seeds and fertilizers are often supplied by the government with limited alternative varieties of seeds and fertilizer. These farmers consider improving farm input supplies to be the most important priority to improve their livelihood and source their water needs for households and animals from the same sources. Therefore, the insignificant difference between the two farming systems is attributed to the same type of input market that they share. Moreover, the design of PPT intervention by *icipe* and its partner in the study area was primarily meant to provide multiple backups in farm input supplies. The finding in this study is consistent with the findings of Heckelman and Smukler [34], who reported no significant difference in the indicator between organic rice systems and conventional rice systems in the Philippines.

Spatial and temporal heterogeneity: The PPT farming systems were better than non-PPT farming systems regarding spatial and temporal heterogeneity indicators of climate resilience. This result implies that PPT farming systems exhibit higher heterogeneity than non-PPT farming systems regarding the landscape, agricultural practices, number of trees and invasive species, perennial trees, and soil types observed in the farmland. Thus, PPT farming systems would have a higher capacity for seed renewal, recovery, and nutrient restoration after disturbances than non-PPT farming systems. This finding is consistent with the advantages of PPT mentioned in relevant scientific literature. Heckelman and Smukler [34] also reported that agroecological farming systems exhibit better spatial and temporal heterogeneity indicators than conventional farming systems. In the FGDs, the farmers in PPT farming systems mentioned that they often employ both the PPT maize farming system and non-PPT maize farming system in parallel, which helps them diversify their cultivation practices. According to them, the companion plants (Brachiaria and Desmodium) serve as terraces against flood erosion, producing a relatively higher degree of spatial heterogeneity in PPT farming systems than in non-PPT farming systems. As perennial crops, companion plants improve the number of trees and percentage of the intercropping practice of PPT farming systems.

Exposure to disturbance: The two farming systems exhibited no significant differences in this indicator and did not allow a controlled amount of invasion of pests and weeds, which is important for the development and selection of plants that exhibit signs of resistance. Unlike the other indicators, PPT farming systems scored a lower level of resilience on this indicator than non-PPT farming systems because PPT farming systems are primarily designed for suppressing pests and weeds. Therefore, temporally rotating PPT farming plots or controlled disadoption of PPT could facilitate the occurrence of a certain controlled amount of invasion of pests and weeds in PPT farming systems. A similar study by Heckelman and Smukler [34] also reported no difference between agroecological farming systems and conventional farming systems concerning exposure to disturbance.

Coupled with local natural capital: Coupled with a local natural capital indicator, farmers in PPT farming systems exhibited higher resilience levels than those in non-PPT farming systems. This finding implies that PPT farming systems have relatively responsible use of local resources through recycling their waste, relying on ecologically healthy soil and water management practices. Thus, PPT farming systems can live within their means and thereby be more sustainable than non-PPT farming systems by reducing the use of pesticides, planting nitrogen-fixing legumes to improve soil quality, and using cover crops to improve water conservation. Our result is consistent with the primary benefits of PPT mentioned in the relevant scientific literature [16]. Our findings thus provide additional empirical evidence of the link between PPT farming systems and sustainable soil and water management practices.

Reflective and shared learning: The two farming systems exhibited no significant differences in the reflective and shared learning indicators. This finding suggests that PPT interventions in the study areas had provided few opportunities to connect PPT farming systems with the local traditional knowledge of the community. A similar study of the rice farming systems in the Philippines reported no difference between organic rice farming systems and conventional rice farming systems [34]. The qualitative insights from the FGDs further supported the results. According to the farmers in the FGDs, PPT conflicts with their traditional knowledge of crop rotation. One of the PPT disadopting farmers stated, "my primary reason for discontinuing using the PPT is that it does not allow us to practice crop rotation, which we traditionally know as an important practice for improving our soil fertility". Many farmers, both PPT adopters and PPT disadopters, agreed with the opinions of the farmers. In this regard, further encouraging field visits and experience-sharing among PPT adopters might be a way forward in supporting learning based on experiences.

Globally autonomous and locally interdependent: The PPT farm system exhibited the highest resilience level for the globally autonomous and locally interdependent indicator compared with the non-PPT farming systems. More global autonomy makes farm systems less vulnerable to forces that are outside their control, while being locally interdependent encourages collaboration and cooperation rather than competition among actors. Thus, the results suggest that PPT farming systems are relatively better for collective actions, use of local crop varieties, use of local animal species, and access to local input and output markets. Heckelman and Smukler [34] found no difference between the two farming systems for the globally autonomous and locally interdependent indicator. In the FGDs, farmers mentioned the limited collaboration among farmers using the PPT farming system in sharing their seeds and seedlings of the companion plants. These farmers further mentioned that improved access to agricultural inputs is the most important area of intervention for enhancing the performance of their farming system and livelihood. In this regard, establishing a local association of PPT users could foster togetherness and intimacy among farmers, improving the likelihood of collective actions such as sharing experiences and agricultural inputs.

Honors legacy: There were no differences between PPT farm systems and non-PPT farm systems for the honors legacy indicator. The dimension measures the engagement of elderly individuals, incorporation of traditional cultivation techniques with modern knowledge, and preservation of traditional knowledge on tree products. The result, the insignificant difference between the two farm systems, is consistent with our expectations and the scientific literature because PPT is a new, emerging, agroecological farming approach that requires deviation from the traditional agricultural intensification practice of farmers.

Building human capital: Regarding building human capital, farmers in PPT farm systems had significantly higher resilience levels than farmers in non-PPT farm systems. This finding implies that PPT farming systems perform better on investments in infrastructure and institutions for the education of children and adults, support for social events, and programs for preserving local knowledge [40]. The higher scores for the farmers in the PPT farm system can be explained by the higher income that they earned from improved maize yield, the sale of seeds for companion plants, and fodder production, as they can reinvest the money in educating children and adults.

Reasonably profitable: The PPT farm system exhibited the highest level of resilience for the reasonably profitable indicator. This finding implies that PPT farming systems allow farmers to make more investments in the future, which adds buffering capacity, flexibility, and building wealth that can be tapped during shocks and stresses. The farmers in the FGDs also mentioned that PPT adoption had increased their income by improving their livestock productivity and seed production for the companion plants.

Regarding the overall resilience capacity of the two farming systems, PPT farming systems exhibited a higher resilience capacity index than non-PPT farming systems. As the resilience capacity index was computed using the previously discussed 13 resilience indicators, the result implies that PPT farming systems are comparatively better than conventional maize farming systems in their overall level of climate resilience. The results from the estimation model also show that households that use the PPT maize farming system are predicted to have a higher resilience capacity index than their counterparts. In general, the analyses at the farming system level and household level in this study support the claim that PPT farming systems are comparatively better than non-PPT farming systems at the level of climate resilience.

In terms of priority for resilience-enhancing interventions, the two farming systems showed no difference in prioritizing changes that would help them to improve their livelihood and resilience to climate change. Farmers in both farm systems ranked access to agricultural inputs, nonfarm income-generating activities, access to output market, livestock health, and water access as the interventions that would most help them to improve their livelihoods and resilience to climate change.

5. Conclusions

Using the SHARP$^+$ approach, we show that PPT maize farming systems have a higher degree of climate resilience than non-PPT or conventional maize farming systems. Our analyses at the farming system and household levels suggest that the PPT-based maize farming system leads to a significantly higher overall climate resilience level as well as many of the agroecological indicators of climate resilience. The farming system-level analysis provides evidence that PPT maize farming systems exhibit a significant impact on eight out of the thirteen agroecological indicators of climate resilience. These results suggest that the PPT farming system alone cannot lead to a higher resilience level for all agroecological resilience indicators. However, PPT farming systems have a higher overall resilience capacity than non-PPT farming systems. The results at the household-level analysis also suggest that households that use the PPT maize farming system are more climate-resilient than their counterparts. Based on these findings, we conclude that PPT has the potential to help to achieve a climate-change-resilient farming system.

6. Practical Implications

The findings of this study provide a pathway for building a climate-resilient food production system in SSA countries. The evidence from this study implies that promoting the PPT farming system among maize-producing farmers strengthens the climate resilience of farming systems. To date, such interventions have been largely focused on improving agricultural productivity through high-external inputs and resource-intensive agricultural systems. This study, however, shows that promoting agroecological approaches such as a PPT-based maize farming system could help in building a climate-resilient and sustainable food production system. Such evidence guides policymakers, non-governmental organizations, and agricultural researchers to include a PPT-based maize farming system as a pathway for building the climate resilience of smallholder farmers.

The findings suggest that solving PPT implementation barriers such as limitations in accessing input and output markets and animal health services deserves concerted efforts and strong national coordination among the actors. These are essential, as some efforts would need collaborations crossing the span of boundaries of the actors.

For agricultural researchers, the results of this study suggest that the climate resilience contributions of PPT can be further improved by leveraging on its weaker dimensions in terms of the thirteen behavioral-based indicators of climate resilience. Research towards improving optimally redundant, exposure to disturbance, reflective and shared learning, globally autonomous and locally interconnected, and honors legacy features in PPT would further enhance its climate resilience contribution. For example, improving the technical backstopping and backups for input accesses could help to improve optimal redundancy. Strengthening field visits and experience-sharing among PPT adopters can improve shared learning. Finding ways to accommodate the traditional cultivation techniques and knowledge of the farmers (e.g., crop rotation practices of the farmers) in PPT farming system would help to amplify the honors legacy features of PPT.

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