Climate-Smart Agriculture and Sustainable Livelihood: A Meta-Analysis

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Abstract

Livelihood capitals are referred to as renewable and non-renewable resources, which can improve the adaptive capacity and contribute to climate-smart agriculture (CSA). The CSA approach includes implementing farmers' technical knowledge and investing in different resources and technologies for the improvement of the farming system. The aim of this study is to examine the impact of livelihood capital on the main elements of the CSA approach through meta-analysis. Therefore, in this study, a meta-analysis is conducted to combine the results of 53 original articles conducted from 1980 to 2021. This study uses weighted meta-regressions to synthesize the global effects of livelihood capitals on climate-smart agriculture (CSA) technology adoption. It quantitatively assesses whether causal links identified in original articles hold true across a wider range of literature. The results show that the combination of natural, financial, social, and human capital affects crop genetic modification, while natural capital solely affects all elements of the CSA. The weighted meta-regression results further indicate that the CSA approach can be globally affected by climatic hazards. Among the spatiotemporal effects of improving livelihood capitals, the greatest impacts were

linked to implementing the farmers' technical knowledge in the African countries for the spatial effect. To enhance farmers' resource-based knowledge, policymakers should consider a multilateral approach that explicitly promotes adaptation strategies like crop diversification. Furthermore, workshops and training sessions can improve farmers' climate perceptions and resilience to climate change effects, based on the results of current study. It is vital to address the challenges in the current livelihood style and explore how the CSA can contribute to improving the situation. Furthermore, livelihood capitals are increasingly appreciated as a necessary element in achieving overall sustainable livelihoods by reducing the destructive effects of climate change.

Keywords: Farmers' technical knowledge; Genetic modification of products; Land use management; Changing crop season; Pest management.

1. Introduction

Climate change negatively impacts agricultural productivity in both developed and developing regions (Chhogyel and Kumar, 2018; Kogo et al., 2021). While farmers are adapting, the effects of climate change may exceed their adaptive capacities and threaten their livelihoods (Dapilah et al., 2019; Fagariba et al., 2018; Schipper, 2020). To this end, farmers should develop adaptation strategies and mitigate the destructive effects of climate change (Dutta et al., 2020; Gebru et al., 2020; Mashizha, 2019). The goals of sustainable development to end poverty and improve the environment are to promote smart farming practices with the climate (Aryal et al., 2018; Aryal et al., 2020; Moya-Clemente et al., 2019). Such practices seek to improve global livelihoods, increase farmers' climate change adaptation and greenhouse gas emission reduction (Abegunde et al., 2019; Maja and Ayano, 2021; Owen, 2020). Climate-smart agriculture (CSA) not only attempts to pursue several development goals, including zero hunger, but also increases agricultural productivity without adversely affecting the environment (Ladha et al., 2020; Zhou et al., 2021).

The CSA can be flexible to achieve the objective of sustainable livelihood by reorienting agricultural development under the real conditions of climate change (Andrieu et al., 2017; Loboguerrero et al., 2019; Mango et al., 2018). Scaling this approach faces challenges such as identifying a set of climate-smart farming options and financial or institutional mechanisms that affect farmers' acceptance and less attention to the local context of the study areas (Adego et al., 2018; Gosnell et al., 2019; Prestele and Verburg, 2019). There is a wrong belief that the CSA can eradicate poverty directly (Hammond et al., 2017; Ho and Shimada, 2019). In fact, adapting to climate change in a way that leads to greater prosperity and escapes from poverty may not be possible for a group of farmers through the CSA (Bhatt et al., 2019; Kongsager, 2017; Oyebola et al., 2021).

However, CSA leads to greater flexibility and sustainability for rural livelihoods (Makate et al., 2019; Sardar et al., 2021). A climate-resistant farming system poses a greater risk to food security and welfare than non-agricultural livelihood strategies, while there are still farmers whose livelihoods are based on high-risk agriculture (Lee, 2021; Odusola, 2021; G. Hermans et al., 2020; Yiridomoh ey al., 2025). Unfavorable current and future rural livelihood conditions make it difficult for some farmers to accept any living opportunity that can be associated with a positive change (Busck and Schmidt, 2020; Córdoba Vargas et al., 2019). Therefore, the term climate-smart may denote focusing on measures to support non-agricultural livelihoods (Azadi et al., 2021; Hellin and Fisher, 2019). If such a livelihood change is positive, providing the necessary conditions for non-agricultural livelihoods needs support (Ma et al., 2018; Wang et al., 2019). In addition, livelihood change should be done in a way that increases household income and security, thus avoiding adverse coping strategies (Azadi et al., 2018; Hellin and Fisher, 2019). In this way, it is vital to address the challenges in the current livelihood style and explore how the CSA can contribute to improving the situation. Furthermore, livelihood capitals are increasingly appreciated as a necessary element in achieving overall sustainable livelihoods by reducing the destructive effects of climate change (Kabonga et al., 2021). Accordingly, livelihood capitals can influence adaptive capacity. Hence, it is imperative to understand the CSA that may occur when improving livelihood capitals (e.g., financial, natural, social, human capitals, and physical) (Azadi et al., 2021). No study has so far quantitatively evaluated the world's climate-smart livelihood capitals. This meta-analysis in this study synthesizes 53 studies from various countries to quantitatively evaluate the impact of livelihood capitals on climate-smart agriculture (CSA) at a global level. The findings can inform agricultural policymakers' decisions on options like investing in crop genetic modification or land use management. This study examines the role of livelihood capitals in Climate-Smart Agriculture (CSA). In this regard, the original articles were critically reviewed regarding the effects of livelihood capitals on the main elements of the CSA (i.e., implementing farmers' technical knowledge, investing in genetic modification of products, progressing land use management, changing crop season, and applying efficient pest management). Hence, this study addresses the following research questions:

I) How do livelihood capitals impact farmers' technical knowledge?

II) How can improving livelihood capitals affect genetic modification of products and crop season?

III) What impacts can livelihood capitals have on land use management and pest management?

IV) What are the spatiotemporal effects of improving livelihood capitals?

Overall, this study develops a theoretical framework on the main elements of the CSA by demonstrating the effects of improving livelihood capitals. Thus, the second section defines the CSA and its elements. The third section describes sustainable livelihoods. The methods section discusses the approaches used to collect and synthesize 53 original articles. The result section reviews the main findings in three categories, including descriptive statistics, weighted meta-regressions, and the CSA and sustainable livelihoods. In the discussion section, the scholarly implications of the main findings are underlined and compared with those of similar studies at the global level. In the end, the conclusion section highlights the key take-home messages for a broader readership with the policy implications of the results.

2. Theoretical background

2.1. Definition of climate-smart agriculture

According to scientific research (e.g., Hasegawa et al., 2018; Karimi et al., 2018; Yoon and Choi, 2019), temperatures are rising due to global climate change, and this is likely to have a negative effect on agricultural production (Makate, 2019; Taylor, 2017; Zougmore et al., 2018). Climate-smart agriculture (CSA) addresses climate change and food security by simultaneously increasing productivity and resilience while reducing greenhouse gas emissions (Bhattacharyya et al., 2020; Mishra et al., 2021). The need for policymaking on the CSA requires increasing food efficiency, sustainable livelihoods of the growing population, mobilizing investment for farmers, and reducing greenhouse gas emissions (Chandra et al., 2017; De Pinto et al., 2020; Heeb et al., 2019). Agriculture is the dominant economic sector in several countries and is vital to meet the livelihood needs of most low-income groups (Gassner et al., 2019; Nhemachena et al., 2018; Rigg et al., 2018). Therefore, the three bases of CSA, including adaptation, mitigation, and food security, can have significant outcomes for low-income farmers (Azadi et al., 2021; Mishra et al., 2021).

In fact, the need for the CSA goes beyond participation in local sustainable development goals, as it has a wider range of influence (Dinesh et al., 2018; Schaafsma et al., 2019; Thornton et al., 2018). Therefore, climate-smart is recognized worldwide as a way to protect the agricultural sector. The effectiveness of climate-smart agricultural policy is limited for a variety of reasons. For example, there are institutional barriers to the adoption and promotion of climate-smart practices in agriculture (Blaser et al., 2018; Totin et al., 2018; Westermann et al., 2018). Climate-smart agricultural interventions need a lot of knowledge, specific location, and significant capacity development (Khatri-Chhetri et al., 2019; Makate, 2020; Partey et al., 2018). Thus, researchers offer that increasing community-based participatory approaches to sustainable agriculture can bring about fair transformation in agriculture (Andreotti et al., 2020; Ioannis et al., 2019). Sustainable farming practices such as conservation agriculture, small-scale irrigation, and soil/water conservation have been implemented for a long time (Findlater et al., 2019; Kassam et al., 2018; Rodenburg et al., 2020; Eze et al., 2022). In general, there are differences of opinion and discussion on the CSA in terms of perception in the world (Amadu et al., 2020; Chandra et al., 2017; Saj et al., 2017).

2.2. Main elements

2.2.1. Implementing farmers' technical knowledge

Most farmers, especially in Asia and Africa, are very poor with limited resources and have been experiencing environmental changes for years (Bezner Kerr et al., 2019; Florini and Pauli, 2018). Farmers have a variety of specialties with a number of practices used to manage the weaknesses of the environment (Giuliani et al., 2017; Rodríguez-Ortega et al., 2018). Such specialties are necessary to address modern needs (i.e., harvest automation, autonomous tractors, and seeding and weeding). Indigenous environmental knowledge of people can offer various ideas and possible options against environmental dangers (Berkes, 2017). Indigenous people have made great strides in the face of natural disasters such as landslides and famines, so they have devised ways to reduce the effects of these disasters (Burson et al., 2018).

2.2.2. Investment in genetic modification of products

Genetic modification is the CSA approach that leads to increasing crop productivity (Singh et al., 2017; Venkatramanan and Shah, 2019). Some beneficial effects of genetic modification in agriculture include reducing food or drug production costs and pesticide requirements, increasing yields, nutrient composition and resistance to pests, and more food quality and food security (Gaitán-Espitia and Hobday, 2020). There is usually a major revolution in agricultural research every 25 years that almost doubles the productivity to feed the growing global population through genetic modification of products (Raman, 2017; Reardon et al., 2018). Genetic modification methods can reduce the risks of environmental conditions by providing new types of plants resistant to heat and salinity stress (Raza et al., 2019). Modified seeds are key elements in protecting plants from pests and environmental threats. Thus, to reduce the incremental risks to plants, it is necessary to develop resistant crop varieties (Devos et al., 2018; Zhang et al., 2018a).

2.2.3. Progressing land use management

Land use management can mitigate climate change effects like floods, droughts, water shortages, and heat stress, while also protecting soil nutrients (Costanza et al., 2020). Appropriate planning of land use such as fixing the production site of plants and animals, changing the concentration of plant foods, and using insect sprays can help decrease the risks of global warming to agriculture (Heeb et al., 2019; Sarker et al., 2019). Improving farmers' activities (i.e., changing irrigation periods or using other elements such as plant nutrients), can ensure soil quality (Chojnacka et al., 2020; Cox et al., 2018).

2.2.4. Changing crop season

Improved agricultural systems include the cultivation of high-yielding varieties, increasing agricultural intensity, and adaptation to different hydrological conditions (Acharjee et al., 2019; Nguyen et al., 2018). The growing season can be adjusted to decrease infertility due to high temperatures, which can match the flowering interval with the last period. Changes in plants or planting time to prevent severe weather events in a year can help reduce the side effects of climate change that are common in semi-arid and arid regions (Waldman et al., 2019; Xu et al., 2020). A longer growing season, resulting from combined spring and late fall conditions, can help mitigate climate change by reducing atmospheric CO2 accumulation (Hou et al., 2021).

2.2.5. Efficient pest management

Agricultural pest management has traditionally been very averse to the environment (Heeb et al., 2019; Sarker et al., 2019). Exterminating pests using chemicals is harmful to humans and other ecosystem organisms (Costa et al., 2019; Van den Brink et al., 2021). Although some countries have banned the use of chemicals (e.g., insecticides, herbicides, and herbal medicines), there are almost no environmentally friendly pesticides. Thus, farmers are forced to apply harmful chemicals to control pests. The CSA provides an opportunity to use environmentally friendly pest management measures such as integrated pest management (Heeb et al., 2019; Santos et al., 2021; Sharifzadeh et al., 2018). Integrated pest management combines biological, cultural, and chemical methods for agricultural pest control. The purpose of this management approach in the context of climate change includes reducing crop losses due to pests, increasing ecosystem services, reducing the intensity of greenhouse gas emissions, and strengthening the resilience of agricultural systems (Heeb et al., 2019).

2.3. Definition of sustainable livelihoods

In recent decades, research on livelihoods to address poverty and improve income internationally has been of particular importance (Agyeman et al., 2019; Feurer et al., 2018). Livelihood refers to a way of earning a living based on capabilities, livelihood capital (i.e., resources, claims, and rights), and activities (Andrews, 2018; Liu et al., 2020). Livelihood capitals include natural capital (i.e., land and garden), physical capital (e.g., agricultural implements), financial capital (i.e., income), social capital (i.e., membership in social institutions), and human capital (e.g., education and training course) (Lin and He, 2021; Mengistu and Assefa, 2020). The set of activities that households select to use livelihood capitals for achieving livelihood goals is called a livelihood strategy (Berchoux et al., 2019; Liu et al., 2020; Xu et al., 2020). Various analytical frameworks have been presented on the subject of livelihood, among which the sustainable livelihood framework is more common (Aazami and Shanazi, 2020; Pasanchay and Schott, 2021; Zhang et al., 2019). In the sense of sustainable livelihoods, households have five types of livelihood capitals, and they are in line with livelihood strategies (choice of agricultural and non-agricultural activities), agricultural policies (subsidies and preferential and low-interest loan policies), and vulnerability context (climatic, economic, and political shocks) (Senapati, 2019; Wang et al., 2019; Zhang et al., 2018b). Five types of livelihood capitals are expected to influence the adoption of livelihood strategies, which ultimately lead to different livelihood outcomes such as increased income, food security, welfare, reduced vulnerability to natural disasters, and environmental improvement (Shinbrot et al., 2019; Zeng et al., 2021). In addition, livelihood outcomes have a greater impact on livelihood capitals (Aazami and Shanazi, 2020).

Livelihood capitals can play a role in taking the appropriate measure to deal with the phenomenon of climate change (Cauchi et al., 2020; Hossain et al., 2020; Islam and Nursey-Bray, 2017). This article examines how livelihood capitals (natural, financial, physical, human, and social) function as adaptive capacities that influence the adoption of Climate-Smart Agriculture (CSA).

2.4. Main elements

2.4.1. Natural capital

Natural capital is a capital that in its role provides natural resources and environmental services for economic production (Ahmed et al., 2020; Keith et al., 2017; Merino-Saum et al., 2018). Some of these capitals provide free goods and services to humans (e.g., rangelands), which are called ecosystem services (Chaudhary et al., 2018). Thus, this capital is the way of thinking about nature as a stock that supplies the benefit flow to the people and the economy.

In general, natural capital consists of three main categories: natural resource stocks, land, and ecosystem (Bateman and Mace, 2020; Leach et al., 2019).

2.4.2. Physical capitals

Physical capital includes tangible objects that are either invested in or applied to produce goods (Levy, 2017). Physical capital items (i.e., manufacturing tools), are also in the fixed capital class, meaning that they are reusable and are not consumed during the production process (Brecher et al., 2018; Franciosi et al., 2020). This capital is the input that is applied at various steps of the production of goods and services. Real property, equipment, and inventory are examples of physical capital (Ronchini et al., 2021).

2.4.3. Financial capitals

Financial capital refers to economic resources that investors use to buy the products they need or provide services to the economy on which their performance is based, such as retail, corporate, investment banking, and etc. (Hota and Mitra, 2021; Khan et al., 2018). Investors use financial capitals to grow, which helps increase their income (Corbet et al., 2018; Davis, 2017). Additional capital is intended to add labor productivity by making companies more productive and efficient. Together with more efficient labor, this leads to economic growth (Zhan and Du, 2020).

2.4.4. Social capitals

Social capital is the network of relations between people who live and work in a specific community and enable the community to function efficiently (King et al., 2019; Masud-All-Kamal and Monirul Hassan, 2018). In this definition, networks can be thought of as real links between groups or individuals. Social capitals can create or destroy a business by strengthening or weakening relationships between members of an association. Social capital is a desire for development, because building and cultivating relationships takes time, and social capital creates a store of generosity in society (Ghahtarani et al., 2019). Creating a wide range of relations can create the conditions for people to progress because they can do things more effectively and efficiently (Cohen, 2018; Nirino et al., 2020).

2.4.5. Human capitals

Human capital is a new term in the economic literature that refers to the academic achievement, knowledge, experience, and skills of the labor force (Flores et al., 2020; Ozkeser, 2019). In this way, this capital allows people to perform their duties more productively (Müller et al., 2018; Nisar et al., 2018). Education is one of the most important sources of the human capital constitution. Investing in education leads to economic development and productivity and therefore generates more income for people (Psacharopoulos and Patrinos, 2018).

3. Methodology

This research used weighted meta-analysis to synthesize the effects of livelihood capitals on climate-smart agriculture (CSA) technology adoption worldwide. Meta-analysis, a statistical approach that synthesizes results from original articles to address new research questions (Pigott and Polanin, 2020), was employed to pool data and quantitatively assess the validity of causal links across a broad range of literature. Meta-regression was then used to explore these links, utilizing the dependent and independent variables detailed in Tables 1 and 2.

Table 1

Dependent variables defined

Dependent variable	Definition
Implementing farmers' technical knowledge	The actual knowledge of farmers that reflects tradition-based experiences and includes newer experiences with modern technologies.
Investing in genetic modification of products	Modification of plant DNA using genetic engineering methods.
Progressing land use management	Focus on the land and how to use it for production, protection, or aesthetic reasons.
Changing crop season	Season change to cultivate specific crops.
Efficient pest management	Process to reduce the number of pests to an acceptable threshold.

Source: Florini and Pauli (2018), Sarker et al. (2019), and Venkatramanan and Shah (2019)

Table 2

Main independent variables coded from the original articles and included in the meta-regression.

Factor	Variable	Description
Livelihood	Livelihood capitals	Dummy variable: If the article focuses on livelihood capitals, including natural, physical, financial, social, and human capitals.
Shock	Climate change	Dummy variable: On climate change.
	Political	Dummy variable: Considering political shocks.
	Economic	Dummy variable: "Addresses economic shocks."
Time	Data gathering year	Continuous variable: Data were collected from 1980 to 2021.
Space	Africa	Dummy variable: If the article focuses on Africa.
	America	Dummy variable: If the article's regional focus is on America.
	Asia	Dummy variable: If the article's regional focus is on Asia.
	Europe	Dummy variable: If the article's regional focus is on Europe.
Type of article	ISI publication	Dummy variable: Published in an ISI Journal.
Methodology applied	Appropriate method	Dummy variable: Captured unobserved heterogeneity.

Source: Meemken (2020) and Pigott and Polanin (2020)

The meta-analysis followed a five-step methodology (Fig. 1), informed by Vesco et al. (2020) and Woodcock et al. (2014): searching, applying inclusion/exclusion criteria, evaluation, data extraction, and synthesis.

3.1. Searching

Turkeš et al. (2021) propose that effective searches for original articles should be comprehensive, systematic, and transparent. Following this framework, this study comprehensively searched ISI Web of Science, Elsevier Science, Springer, ProQuest, Oxford University Press, and SID databases for original articles published between 1980 and 2021. Furthermore, the main keyword used to obtain the data was 'livelihood capitals' along with other relevant concepts including 'natural capital', 'physical capital', 'financial capital', 'social capital', and 'human capital'. These keywords were then combined with 'climate-smart agriculture', 'technical knowledge', 'product genetic modification', 'land use management', 'changing crop season', and 'pest management'. Our initial search resulted in about 7,430 original articles.

3.2. Inclusion and exclusion criteria

Following an initial comprehensive search yielding numerous articles, this study established inclusion and exclusion criteria to determine eligibility for our meta-analysis. Clear definition of these criteria is crucial, as it impacts the meta-analysis results. Consistent with best practices for transparency (Pigott and Polanin, 2020), this study applied specific inclusion and exclusion criteria. Articles focusing on the effects of livelihood capitals on CSA technology adoption were extracted based on titles and abstracts. In this meta-analysis, dependent variables included farmers' technical knowledge, investment in genetic modification, land use management, crop season changes, and pest management (Table 1). After excluding articles focusing on the inverse impact of CSA on sustainable livelihoods, 136 journal articles remained. Then, the "data availability" criterion was applied, and articles that reported effect sizes as percentage differences between adopters and non-adopters of climate smart technology on various CSA dimensions were selected. Percentage probabilities offer two benefits: ease of interpretation and calculation without variance measures, which are often missing from original articles. Consequently, the number of main articles (Appendix A) decreased because quantitative effect size data became available for variables related to 53 articles.

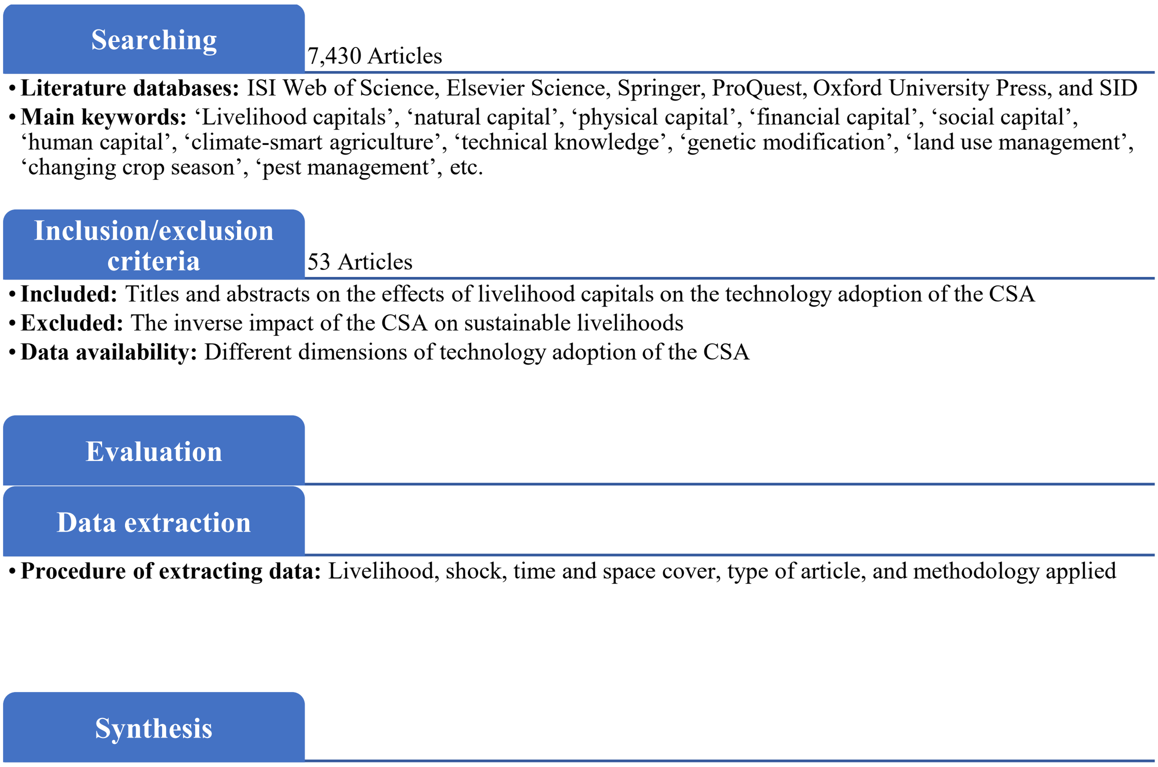

Fig. 1. The flowchart of research methodology steps.

Source: Study findings

3.3. Evaluation

Original articles varied methodologically (Meemken, 2020; Vesco et al., 2020). This meta-analysis assessed the methodological quality of the original articles using an explanatory variable (Table 2). To ensure uniform effect sizes and address potential heterogeneity, percentage differences were used for dependent variables in the meta-regression. Average effect sizes were calculated using sample-size weighted results from original articles (Meemken, 2020). In this analysis, explanatory variables in meta-analysis are weighted based on the number of significant occurrences in the total relationships, and their degree of importance is determined (Neves et al., 2024).

3.4. Data extraction

Variations in data quantity and quality across original articles addressing the same issue can significantly impact meta-analysis findings. Therefore, a clearly defined and consistent data extraction procedure is crucial (Pigott and Polanin, 2020; Vesco et al., 2020). To standardize effect sizes, percentage differences in livelihood capitals between adopters and non-adopters were calculated for all dependent variables, using data extracted from 53 selected articles and following the methods of Klümper and Qaim (2014) and Meemken (2020). This approach offers two key advantages: ease of interpretation and applicability even when original articles lack variance measures. Independent variables, based on Pigott and Polanin (2020), encompassed livelihood, shock, time and space cover, article type, and methodology (Table 2). Qualitative data for each factor were aggregated and represented as continuous or dummy variables, with dummy variables coded as 1 if the article addressed the feature and 0 otherwise.

3.5. Synthesis

This meta-analysis synthesizes the effect of livelihood capital adoption on key elements of climate-smart agriculture (CSA), following best practices to minimize measurement bias (Klümper & Qaim, 2014; Meemken, 2020). This meta-regression used English-language peer-reviewed articles in international journals to estimate the mean effects and quantitative composite of median effects. These articles examined the climate change impacts of smart agriculture through the adoption of livelihood capital.

Meta-regressions were run using Stata version 17 (Stata Corp, College Station, TX, USA).

Table 3 indicates the statistical description of the studied variables in the meta-analysis. On average, livelihood capitals accounted for 41%, while the impacts of various shocks (i.e., climate change, political, and economic) averaged 27%, 28%, and 47%, respectively (Table 3). According to Table 3, around 41% of original articles were positioned in the Americas, and the year of implementation of studies has an average of 2017. Finally, nearly 91% of the original articles were published in an ISI journal, and 3% of the original articles addressed the heterogeneity in their methodology. Hence, these studies were considered unbiased (Wooldridge, 2009).

Table 3

Statistical description of variables in the meta-analysis

Variable	Description	Mean	Std. dev	Min	Max
Livelihood					
Livelihood capitals	Equal to one when the livelihood capitals are analyzed	0.413	0.578	0	1
Shock					
Climate change	Equal to one when the climate change is analyzed	0.269	0.437	0	1
Political	Equal to one when the political is analyzed	0.283	0.179		
Economic	Equal to one when the economic is analyzed	0.468	0.472	0	1
Time					
Data gathering year	The time of the implementation of paper	2017	7.56	1980	2021
Space					
Africa	Equal to one when the article position is located in Africa	0.273	0.369	0	1
Americas	Equal to one when the article position is located in the Americas	0.413	0.598	0	1
Asia	Equal to one when the article position is located in Asia	0.144	0.211	0	1
Europe	Equal to one when the article position is located in Europe	0.284	0.369	0	1
Effectiveness					
Publication type	Equal to one when the publication type deals with an ISI Journal	0.914	0.961	0	1
Methodology type	Equal to one when the method is concerned with the identification of heterogeneity	0.031	0.145	0	1

Source: study findings

4. Results

Figure 2 shows the distribution of original articles on livelihood capitals and external shocks from 1980 to 2021. The number of articles varied annually, peaking in 2020. The fewest articles were published between 1980 and 2000, while the most were published between 2009 and 2021. Data related to livelihood capitals and external shock began to grow following the perception of climate change in the world after 2000, with an increasing rate for original articles.

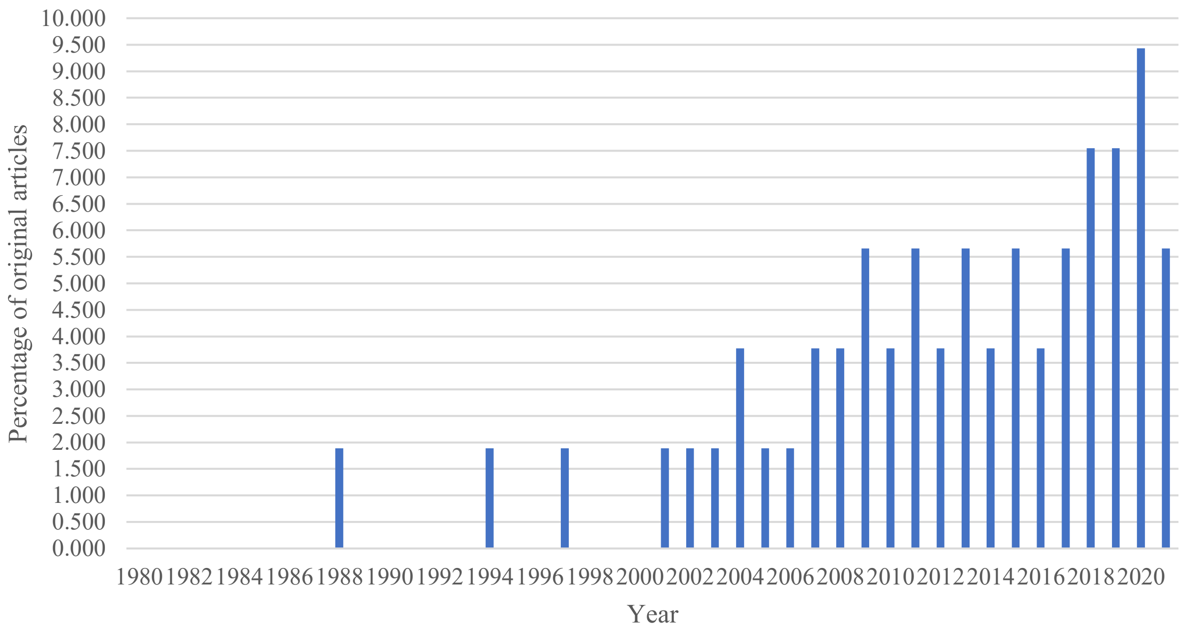

Fig. 2. The Distribution of original articles over the years (1980–2021) regarding the effects of livelihood capitals and external shock on the CSA.

Source: Study findings

Figure 3 shows the proportion of livelihood capitals and external shocks across various continents. As shown in Figure 3, the highest proportion of livelihood capitals and external shocks was investigated in Asia, which reports around 36% of all ones, followed by Europe (28%) and the Americas (19%). The lowest proportion of livelihood capitals and external shock was obtained in Africa, which reported 17%.

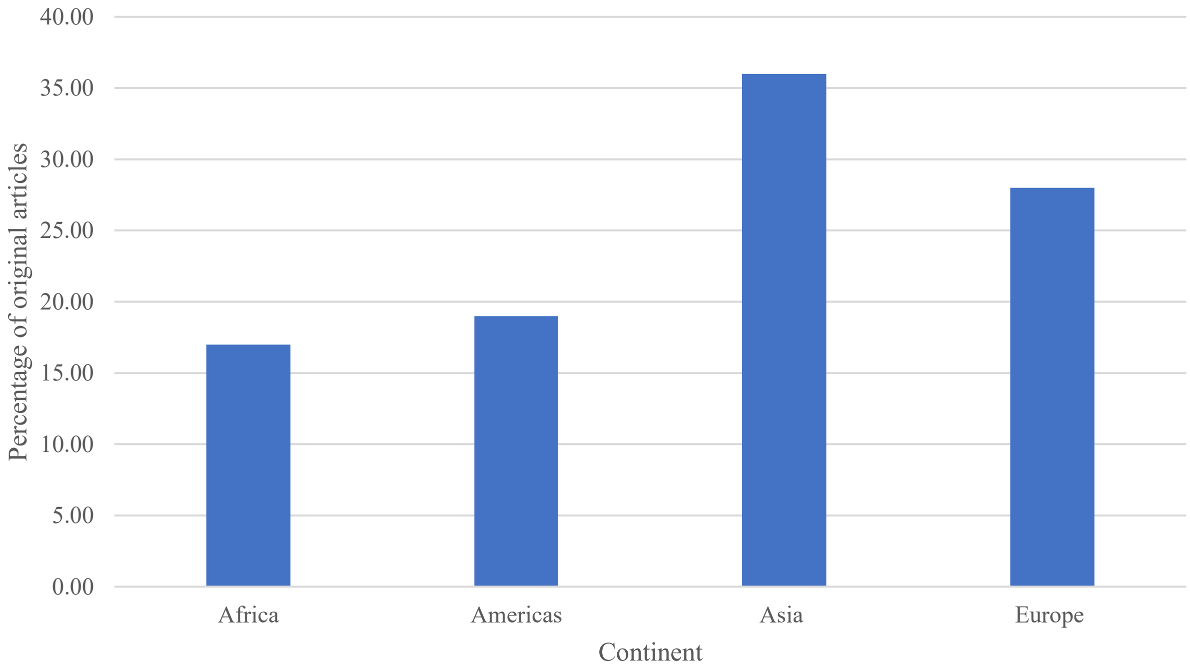

Fig. 3. Proportion of livelihood capitals and external shocks considered across various continents.

Source: Study findings

Table 4 offers five livelihood capitals applied for meta-analysis. The class with the highest number of observations included human capital (85 observations). Then, financial capital with 79 observations and natural capital with 54 observations were ranked. Hence, these classes of livelihood capitals were studied more in the world.

Table 4

Classes of livelihood capitals under meta-analysis

Class	Number of observations
Human capital	85
Financial capital	79
Natural capital	54
Physical capital	48
Social capital	43

Source: Study findings

The original articles focused on various external shocks, including climate change and political and economic shocks (Table 5). The reviewed articles, which dealt with the effects of climate variables, have been classified in a group called climate change (including 28 articles), while other impacts are grouped as political and economic shocks (consisting of 14 and 11 articles, respectively).

Table 5

Overview of original articles due to external shock.

Shock	Number of original articles	Percentage of original articles
Climate change	28	52.8
Political shock	14	26.4
Economic shock	11	20.8

Source: Study findings

Figure 4 illustrates the proportion of original articles that noted indicators across the CSA. Figure 4 indicates diverse aspects of the CSA being researched, with some getting more attention than others. Specifically, the type with the highest proportion of original articles is rated for changing crop season, accounting for 30% of the studies. Other types with considerable review proportions include progressing land use management and efficient pest management, representing 23% and 19% of the total studies, respectively.

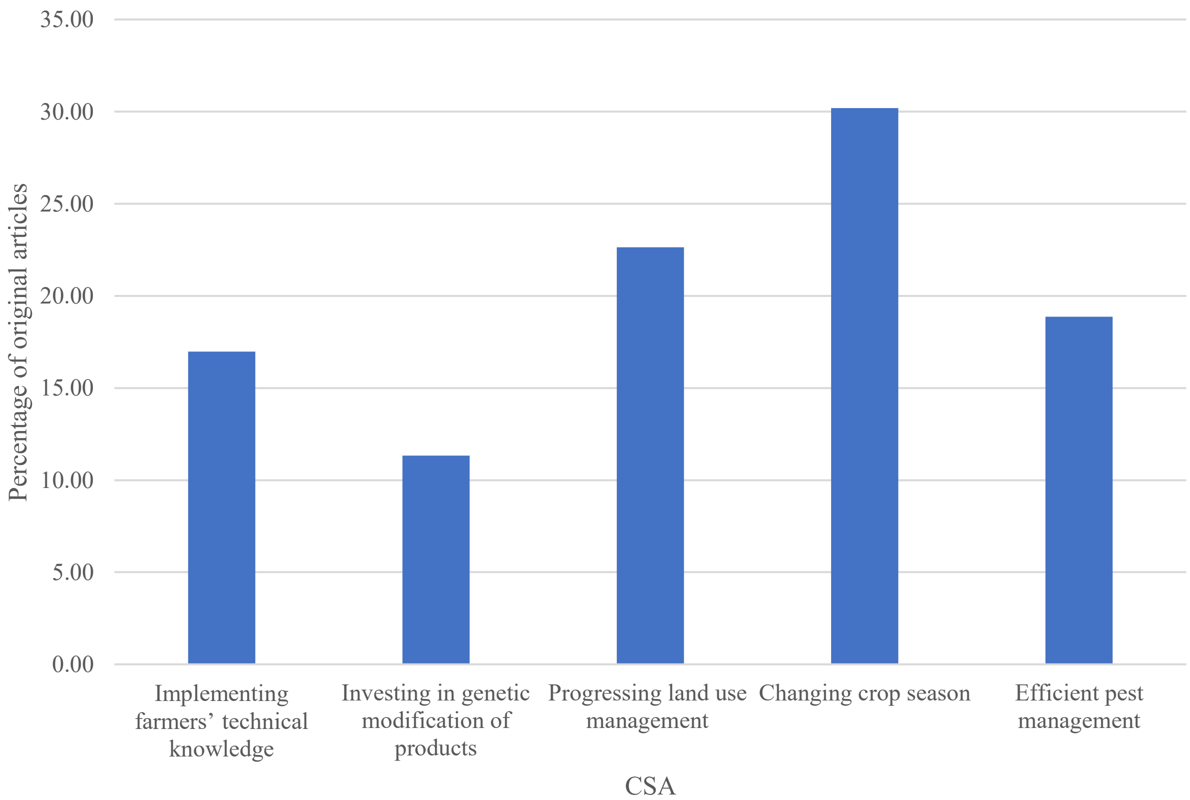

Fig. 4. The proportion of original articles noting the aspects of the CSA.

Source: Study findings

4.2. Meta-regressions

As shown in Table 6, the R^2 values range from 0.89 (first column) to 0.99 (third and fourth columns), indicating that the explanatory variables in the meta-regressions explain a substantial share of the variance in CSA impact. Based on the results, the main variable of livelihood capital has significant effects on the main elements of the CSA. Those effects include investing in genetic modification of products (mean effect: 0.15, $P \leq 0.10$), progressing land use management (mean effect: 0.12, $P \leq 0.05$), changing crop season (mean effect: 0.11, $P \leq 0.05$), and efficient pest management (mean effect: -0.16, $P \leq 0.05$). In addition, climate change shock has significantly negative impacts on the main elements of the CSA. Those effects include progressing land use management (mean effect: -0.09, $P \leq 0.10$), changing crop season (mean effect: -0.11, $P \leq 0.05$), and efficient pest management (mean effect: -0.11, $P \leq 0.10$). Moreover, political shocks significantly decrease factors such as implementing farmers' technical knowledge (mean effect: -0.21, $P \leq 0.05$), progressing land use management (mean effect: -0.11, $P \leq 0.05$), changing crop season (mean effect: -0.14, $P \leq 0.01$), and efficient pest management (mean effect: -0.14, $P \leq 0.05$). However, economic shock has significantly decreased the progress of land use management (mean effect: -0.09, $P \leq 0.05$) and changing crop season (mean effect: -0.12, $P \leq 0.01$).

The data collection year significantly affects key aspects of the CSA. Those effects include implementing farmers' technical knowledge (mean effect: 0.01, $P \leq 0.10$), investing in genetic modification of products (mean effect: 0.02, $P \leq 0.05$), progressing land use management (mean effect: 0.02, $P \leq 0.05$), changing crop season (mean effect: 0.02, $P \leq 0.05$), and efficient pest management (mean effect: 0.01, $P \leq 0.01$). It means that if the original article used initial data in the recent decade, livelihood capitals cause an increase of about 1%, 2%, 2%, 2%, and 1% in implementing farmers' technical knowledge, investing in genetic modification of products, progressing land use management, changing crop season, and efficient pest management, respectively.

For spatial effects, different continents have a significant influence on various climate-smart agricultural impacts of improving livelihood capitals. Studies in Africa and the Americas demonstrate that CSA implementation impacts farmers' technical knowledge (mean effect: 0.23, $P \leq 0.01$ and mean effect: -0.19, $P \leq 0.05$), investing in genetic modification of products (mean effect: 0.21, $P \leq 0.01$ and mean effect: -0.15, $P \leq 0.05$), progressing land use management (mean effect: 0.21, $P \leq 0.01$ and mean effect: -0.14, $P \leq 0.01$), changing crop season (mean effect: 0.22, $P \leq 0.01$ and mean effect: -0.16, $P \leq 0.05$), and efficient pest management (mean effect: 0.18, $P \leq 0.01$ and mean effect: -0.16, $P \leq 0.05$). This means that if the original article was performed in Africa, livelihood capitals cause an increase of about 23%, 21%, 21%, 22%, and 18% in implementing farmers' technical knowledge, investing in genetic modification of products, progressing land use management, changing crop season, and efficient pest management, respectively. In the Americas, livelihood capitals cause a decrease of about 19%, 15%, 14%, 16%, and 16% in implementing farmers' technical knowledge, investing in genetic modification of products, progressing land use management, changing crop season, and efficient pest management, respectively.

In general, the type of methodology affects implementing farmers' technical knowledge (84%), investing in genetic modification of products (74%), progressing land use management (65%), changing crop season (67%), and managing pest efficiently management (75%) (Table 6). Additionally, the statistically insignificant coefficients for publication type in Table 6 suggest that original articles published in ISI journals do not significantly impact CSA.

Table 6
Effective factors in weighted meta-regressions

Factor	Variable	The main elements of the CSA				
		Implementing farmers' technical knowledge	Investing in genetic modification of products	Progressing land use management	Changing crop season	Efficient pest management
Livelihood	Livelihood capitals	-0.02	0.15*	0.12**	0.11**	-0.16**
		(0.13)	(0.08)	(0.06)	(0.05)	(0.07)
Shock	Climate change	0.17	0.06	-0.09*	-0.11**	-0.11*
		(0.11)	(0.07)	(0.05)	(0.05)	(0.06)
	Political	-0.21**	0.09	-0.11**	-0.14***	-0.14**
		(0.09)	(0.08)	(0.05)	(0.05)	(0.07)
	Economic	0.12	0.06	-0.09**	-0.12***	0.07
		(0.08)	(0.07)	(0.04)	(0.04)	(0.06)
Time	Data gathering year	0.01*	0.02**	0.02**	0.02**	0.01***
		(0.01)	(0.01)	(0.01)	(0.01)	(0.01)
Space	Africa	0.23***	0.21***	0.21***	0.22***	0.18***
		(0.09)	(0.06)	(0.04)	(0.04)	(0.05)
	America	-0.19**	-0.15**	-0.14***	-0.16**	-0.16**
		(0.09)	(0.06)	(0.05)	(0.05)	(0.06)
	Asia	-0.10	-0.03	0.01	-0.01	-0.06
		(0.08)	(0.04)	(0.03)	(0.03)	(0.03)
	Europe	-0.11	-0.22**	-0.19***	-0.17***	-0.17**
		(0.08)	(0.09)	(0.06)	(0.06)	(0.08)
Effectiveness	Publication type	-0.13	-0.08	-0.06	-0.05	-0.10
		(0.37)	(0.25)	(0.20)	(0.20)	(0.23)
	Methodology type	0.84***	0.74***	0.65***	0.67***	0.75***
		(0.10)	(0.06)	(0.04)	(0.04)	(0.05)
Constant		-23.47*	-21.35**	-15.48**	-16.20**	-19.90**
		(14.79)	(10.97)	(6.79)	(6.45)	(8.83)
R^2		0.89	0.95	0.99	0.99	0.96
Number of observations		57	117	182	184	154

Note: The standard errors are shown in parentheses
* $P \leq 0.10$
** $P \leq 0.05$
*** $P \leq 0.01$
Source: Study findings

4.3. Climate-smart agriculture and sustainable livelihoods

The mean effects of improving livelihood capitals on the main elements of the CSA are indicated in Table 6. Improving livelihoods has a positive and significant effect on the average investment in crop genetic improvement (mean effect: 0.15, $P \leq 0.10$) (Table 6). This means that the modification of plant DNA by improving livelihood capitals is increased by about 15%. Furthermore, improving livelihood capitals seems to have a significant effect on the mean of progressing land use management (mean effect: 0.12, $P \leq 0.05$) (Table 6). Thus, natural and non-natural capitals can significantly improve land use for production, protection, or aesthetic reasons. As shown in Table 6, improving livelihood capitals shows a significantly positive effect on the mean of changing crop season (mean effect: 0.11, $P \leq 0.05$). Thus, livelihood capitals cause an increase of about 11% in the season change to cultivate specific crops. Furthermore, the improvement of the livelihood capitals has a significant positive impact on pest management (mean effect: -0.16, $P \leq 0.05$) (Table 6), which means that efficient pest management could be achieved with improved livelihood capitals by about 16%. In other words, increasing the livelihood capitals causes a decrease in the number of pests to an acceptable threshold.

4.3.1. Climate-smart agriculture and natural capital

Figure 5 shows the average impact of improving natural capital on the main elements of the CSA. Those effects include implementing farmers' technical knowledge (median effect: 4.3, $P \leq 0.05$), investing in genetic modification of products (median effect: 6.8, $P \leq 0.10$), progressing land use management (median effect: 25.6, $P \leq 0.05$), changing crop season (median effect: 22.2, $P \leq 0.01$), and efficient pest management (median effect: 8.9, $P \leq 0.10$). Thus, improving natural capital causes an increase of about 4%, 7%, 26%, 22%, and 9% in implementing farmers' technical knowledge, investing in genetic modification of products, progressing land use management, changing crop season, and efficient pest management, respectively. Therefore, by increasing these key elements, it will be possible to achieve the CSA. It can be concluded that the improvement of natural capital can promote adaptation to climate change. These figures support the meta-regression findings (Table 6) and indicate that improving livelihood capital enhances CSA. According to Figure 5, the average percentage of progressive user management difference between the natural capital of the owner and non-owner was calculated to be 25.6%. The median percentage differences of other elements were obtained lower (Fig. 5). Furthermore, the median effect of improving natural capital on progressing land use management is about 83%, 73%, 13%, and 65% higher than the median effects on implementing farmers' technical knowledge, investing in genetic modification of products, changing crop season, and efficient pest management, respectively.

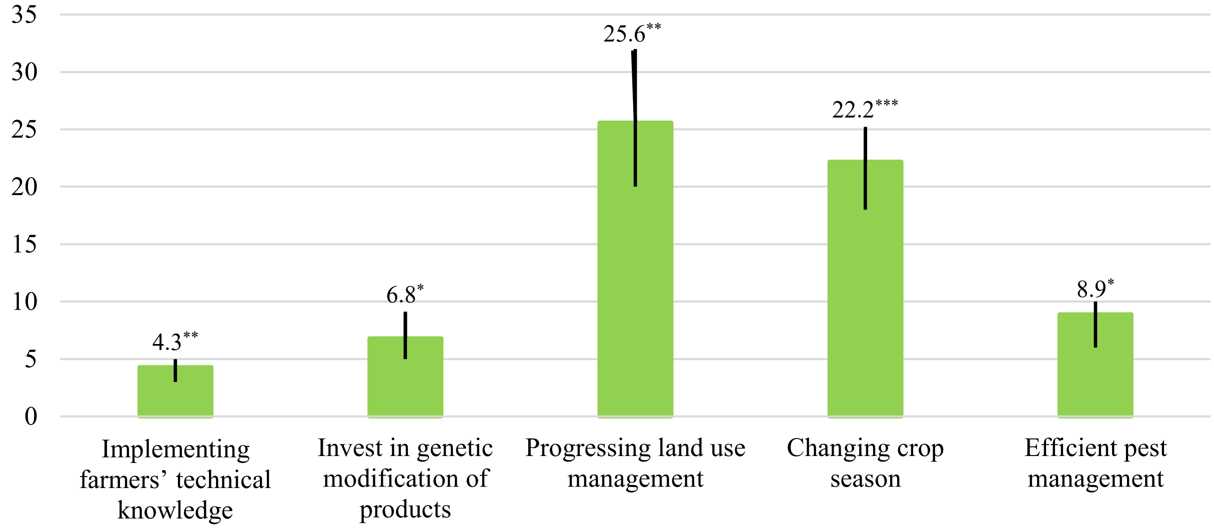

Fig. 5. The median effects of improving natural capital on the main elements of the CSA.

Note: The median percentage differences between owning and not owning natural capital are shown.

*, **, and *** show significance at $P \leq 0.10$, $P \leq 0.05$, and $P \leq 0.01$, respectively.

Source: Study findings

4.3.2. Climate-smart agriculture and physical capital

Figure 6 shows the average impact of improving physical capital on changing crop season (median effect: 16.7, $P \leq 0.01$) and efficient pest management (median effect: 7.2, $P \leq 0.10$). As the results show, improving physical capital can change the median crop season and boost the median pest management, which confirms the results of the weighted meta-regression. The average percentage difference between crop season changes and efficient pest management between owner and non-owner physical capital was about 17% and 7%, respectively (Fig. 6). Furthermore, as shown in Figure 6, the median effect of improving the physical capital on those variables is significant.

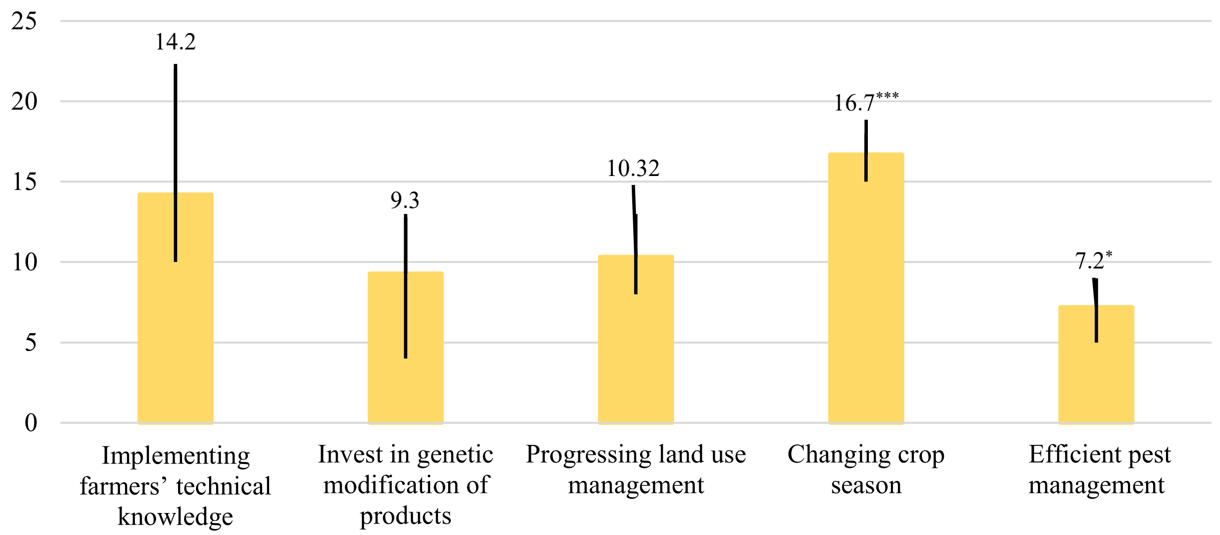

Fig. 6. The median effects of improving physical capital on the main elements of the CSA.

Note: The median percentage differences between owning and not owning physical capital are shown.

*, and *** show significance at $P \leq 0.10$, and $P \leq 0.01$, respectively.

Source: Study findings

4.3.3. Climate-smart agriculture and financial capital

The median effects of improving financial capital on investing in genetic modification of products (median effect: 13.4; $P \leq 0.05$), progressing land use management (median effect: 9.3, $P \leq 0.10$), and changing crop season (median effect: 13.2, $P \leq 0.05$) are significant (Fig. 7). Consistent with the weighted meta-regression (Table 6), these results indicate that improving livelihood capital affects the main elements of CSA, with the most significant effect observed in investments related to the genetic modification of products (Fig. 7). The average percentage difference of investment in genetic modification of products between owned and non-owned financial capital was 13.4%. Also, the average percentage difference between land use management progress and crop season change between owner and non-owner financial capital was 9.3% and 13.2%, respectively.

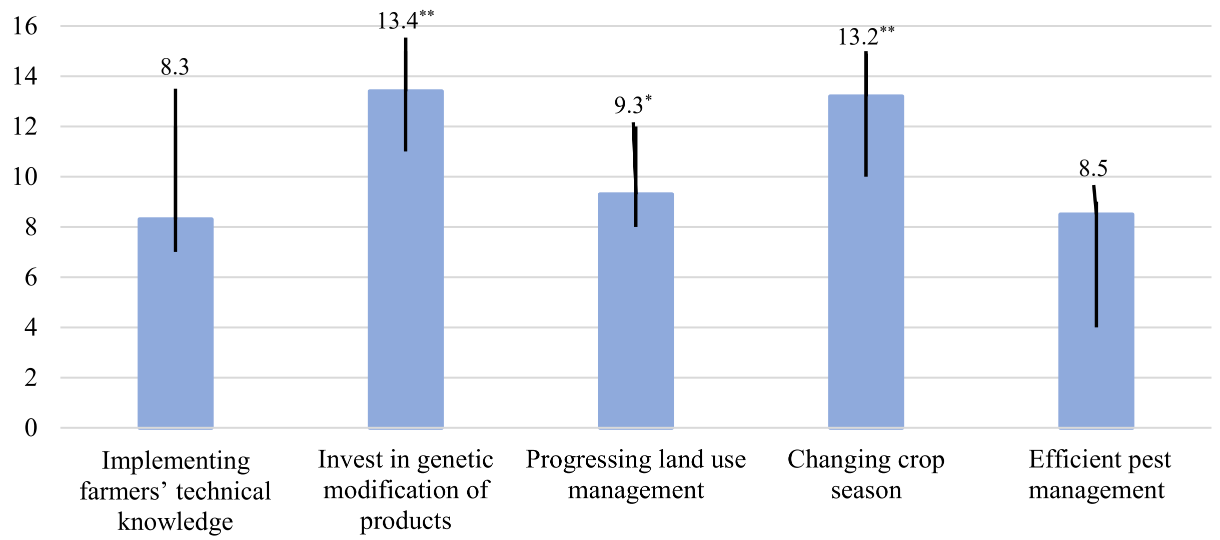

Fig. 7. The median effects of improving financial capital on the main elements of the CSA.

Note: The median percentage differences between owning and not owning financial capital are shown.

*, and ** show significance at $P \leq 0.10$, and $P \leq 0.05$, respectively.

Source: Study findings

4.3.4. Climate-smart agriculture and social capital

Figure 8 shows the average impact of improving social capital on implementing farmers’ technical knowledge (median effect: 15.2, $P \leq 0.01$), investing in genetic modification of products (median effect: 12.3, $P \leq 0.01$), and progressing land use management (median effect: 10.8, $P \leq 0.01$). As the results show, improving social capital can change the average technical knowledge of farmers, increase the average investment in genetic modification of crops, and improve the average progress in land use management, which confirms the results of regression (Table 6). The average percentage difference between the implementation of farmers' technical knowledge, investment in genetic modification of crops and the promotion of land use management between ownership and non-ownership of social capital was about 15, 12 and 11 percent, respectively (Fig. 8). Furthermore, as shown in Figure 8, the median effect of improving the social capital on those variables is significant.

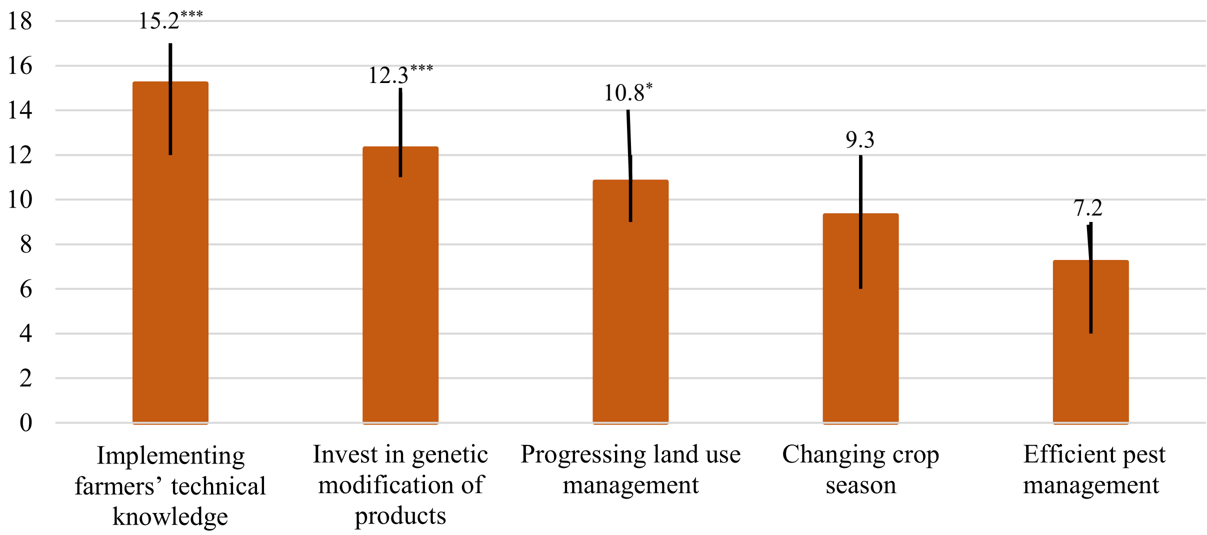

Fig. 8. The median effects of improving social capital on the main elements of the CSA.

Note: The median percentage differences between owning and not owning social capital are shown.

*, and *** show significance at $P \leq 0.10$, and $P \leq 0.01$, respectively.

Source: Study findings

4.3.5. Climate-smart agriculture and human capital

The median effects of improving human capital on implementing farmers' technical knowledge (median effect: 18.2, $P \leq 0.01$), investing in genetic modification of products (median effect: 15.3, $P \leq 0.05$), and changing crop season (median effect: 17.6, $P \leq 0.10$) are significant (Fig. 9). Consistent with the weighted meta-regression (Table 6), these results demonstrate that improving livelihood capitals significantly impacts CSA elements, with the greatest effect observed in implementing farmers' technical knowledge (Fig. 9). The average difference in the implementation of farmers' technical knowledge between owner and non-owner human capital was calculated to be 18.2%. In addition, the average percentage of investment difference in genetic modification of crops and change of crop season between owner and non-owner human capital was 15.3% and 17.6%, respectively.

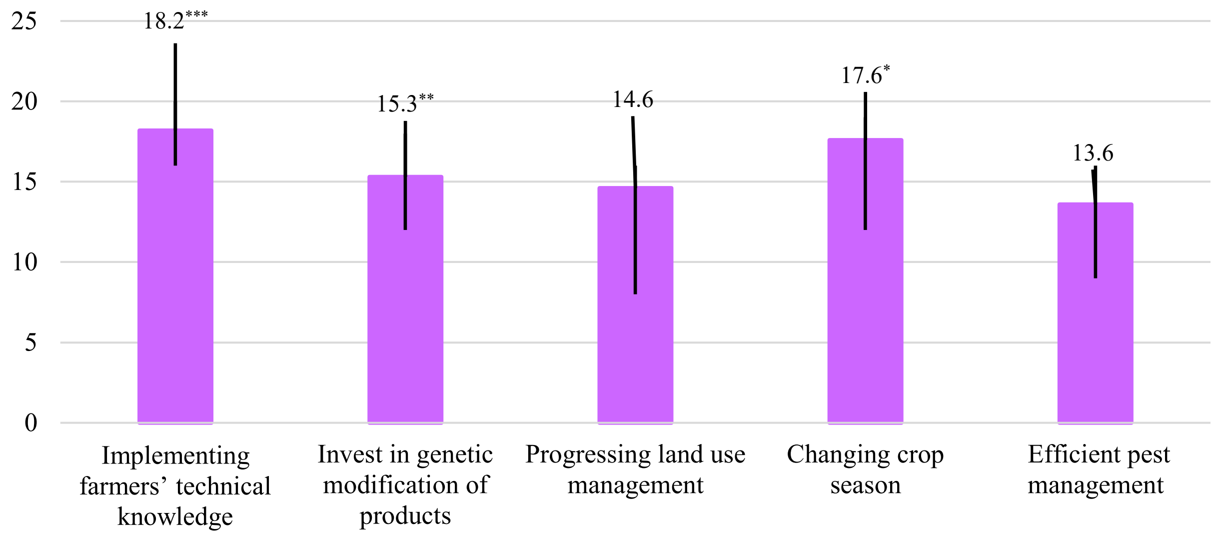

Fig. 9. The median effects of improving human capital on the main elements of the CSA.

Note: The median percentage differences between owning and not owning human capital are shown.

*, **, and *** show significance at P ≤ 0.10, P ≤ 0.05, and P ≤ 0.01, respectively.

Source: Study findings

5. Discussion

As the findings of this study show, climate change and political shocks have significant effects on the main elements of CSA. Climate change can decrease the mean of progressing land use management, changing crop season, and managing pests efficiently by about 9%, 11%, and 11%, respectively. Political shocks reduce the four elements of implementing farmers' technical knowledge, progressing land use management, changing crop season, and efficient pest management by approximately 21%, 11%, 14%, and 14%, respectively. However, economic shocks just decrease the progress in land use management and changing crop season by nearly 9%, and 12%, respectively. The temporal effects are significant in the main elements of the CSA. Moreover, African countries show the largest spatial effects on the main elements of the CSA (e.g., implementing farmers' technical knowledge, investing in genetic modification of products, progressing land use management, changing crop season, and efficient pest management). The results of the contribution of livelihood capitals to the main elements of the CSA are discussed in detail in the following sections.

5.1. Farmers' technical knowledge

The results indicated that natural, social, and human capitals can contribute to the median of farmers' technical knowledge, by 4.3%, 15.2%, and 18.2%, respectively. Therefore, livelihood capitals in the form of natural, social, and human capitals can improve farmers' technical knowledge. Hence, due to the large standard error, the average impact of owning physical capital and financial capital on farmers' technical knowledge is negligible compared to not owning those capitals. The results of other studies such as Van den Berg et al. (2020) and Yang et al. (2018) are in line with the findings of the current study. This result is consistent with the results of Van den Berg et al. (2020). Van den Berg et al. (2020) conducted a study on the farmer field school approach in order to train farmers to make decisions in a variety of changing conditions. This school showed its potential to increase the human, social, natural, and financial capitals of rural societies.

The results showed that in order to clarify the interactions between livelihood capitals and the impact of policies and institutional and external environments, in-depth case studies are needed to adjust school interventions to optimize their impact. Ultimately, these types of schools can be effective in achieving the goals of sustainable development. Yang et al. (2018) found that traditional culture and information technology, in relation to livelihood capitals, play a key role in agricultural livelihoods. Their study of Chinese rice terrace systems revealed that traditional agricultural knowledge discourages farming households from becoming part-time, suggesting that strengthening cultural capital—specifically farmers' understanding of this knowledge—is crucial for the continued preservation of these systems.

5.2. Genetic modification of products and changing crop season

The results showed that natural, financial, social, and human capitals can affect the median of genetic modification of products, by 6.8%, 13.4%, 12.3%, and 15.3%, respectively. Therefore, natural and non-natural capitals can increase the modification of plant DNA using genetic engineering methods. Furthermore, natural, physical, financial, and human capitals can change the median of crop season, by 22.2%, 16.7%, 13.2%, and 17.6%, respectively. However, due to the large standard error, the average effects of owning physical and social capital on investing in genetically modified crops and changing the growing season are negligible compared to the non-acceptance of such capital. Weighted meta-regression analysis indicates that enhancing livelihood capital positively influences investment in product genetic modification and crop season changes. However, the mean effects of improving livelihood capital are lower than the median effects of owning such capital. This suggests that livelihood platforms can significantly contribute to crop genetic modification and seasonal adaptation for specialized cultivation. The findings on the impact of improving livelihood capitals on genetic modification of products and crop scheduling can be confirmed by Kuang et al. (2020) and Shinbrot et al. (2019). Kuang et al. (2020) showed that the main livelihood risks in agricultural production in China include natural and market risks. The results of Shinbrot et al. (2019) on the adaptation strategies by farmers in Mexico showed that diversity of crop species and changing planting dates are among the most common climate-smart strategies. Natural capital in the form of agricultural land ownership, physical capital including farm equipment, and social capital in terms of group membership affect farmers' adaptation to climate change. In addition, better understanding of climate variables by farmers affects their likelihood of adaptation.

5.3. Land use management and pest management

The results showed that natural, financial, and social capitals can affect the median of land use management, by 25.6%, 9.3%, and 10.8%, respectively. Therefore, the livelihood platform can improve land use for production, protection, or aesthetic reasons. Furthermore, natural and physical capitals can control the number of pests to an acceptable threshold, by 8.9%, and 7.2%, respectively. Weighted meta-regression results indicate that improving livelihood capitals positively impacts both land use and pest management. The greater mean effects compared to median effects suggest that actively improving livelihood capitals has a more substantial impact than simply possessing them. Overall, livelihood capitals are crucial for advancing land use management and efficient pest management. The findings on the impact of improving livelihood assets on land use management and pest management can be consistent with the results of studies by Kuang et al. (2019) and Zeveld et al. (2000), who examined the relationship between livelihood assets and farmers' adaptation strategies to climate change in China. Livelihood capital in the form of natural and unnatural capitals has played an important role in adopting adaptation strategies. Zeweld et al. (2000) showed that human capital (in the form of education, labor supply, agricultural extension, risk reduction attitudes, and agricultural experience), natural capital (in the form of soil conditions), and social capital are factors that influence farmers' decisions in adopting adaptation methods. Climate-smart strategies are adopted individually or jointly from sustainable integrated practices that increase crop production, household revenue, and capitals.

6. Conclusion

The effects of climate change can be reduced by the application of the CSA approach such as improving land use management, following new agricultural technologies, and applying effective management techniques. Therefore, following the perspective of CSA, sustainable agriculture is based on integrated management by agricultural agents. Livelihood capitals can significantly improve farmers' technical knowledge, facilitating the adoption of climate-smart technologies. Furthermore, these capitals significantly influence genetic modification of products and changes in crop seasons. While the combination of natural, financial, social, and human capitals affects genetic crop modification, owning them affects the change of crop season. To address the third research question, the results showed that the livelihood platform has a positive and significant impact on land use management and pest management. Thus, the livelihood base can improve land use management and pest control practices. The fourth question of this research examined the spatial-temporal effects of the ownership of livelihood assets. Among the temporal effects of capital improvements, the most positive effect is on farmers' technical knowledge implementation. According to the results, European countries have the greatest positive impact of capital, while Asian countries may feel the least positive effect of capital on investment in crop genetic improvement. Finally, the findings of this study indicate that improving livelihood assets can be effective for the main elements of CSA. Furthermore, climate change and political shocks can be unfavorable to achieve perfect adaptation to climate change in the world. Policy-makers should consider the global perspectives of the livelihood platform based on the benefits. Probably the most beneficial effect of livelihood capitals is that it improves land use for farmers in the face of climate change. In addition, livelihood capitals enable the achievement of sustainable goals and enable farmers to engage in activities that will increase resilience to climate change in the future. Finally, changing the growing season and increasing the length of the growing season reduce the risk of flooding and crop destruction. In addition, the CSA enables development and food security by increasing productivity and incomes and enhancing the resilience of livelihoods. Based on the findings of this study, it is recommended that policymakers enhance farmers' climate knowledge and adaptation by explicitly promoting adaptation strategies through climate training workshops. A multifaceted approach to improving farmers' resources is also recommended by implementing programs such as crop diversification. Therefore, it is recommended that future studies focus on land use of natural capital and examine resilience enhancement through adaptation strategies. In addition, various cost reduction methods, including fixed and variable costs, should be considered to promote future livelihood capitals. A limitation of this study was its focus on English-language articles, which may have included articles on climate-smart agriculture for sustainable livelihoods in other languages.

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Appendix A

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